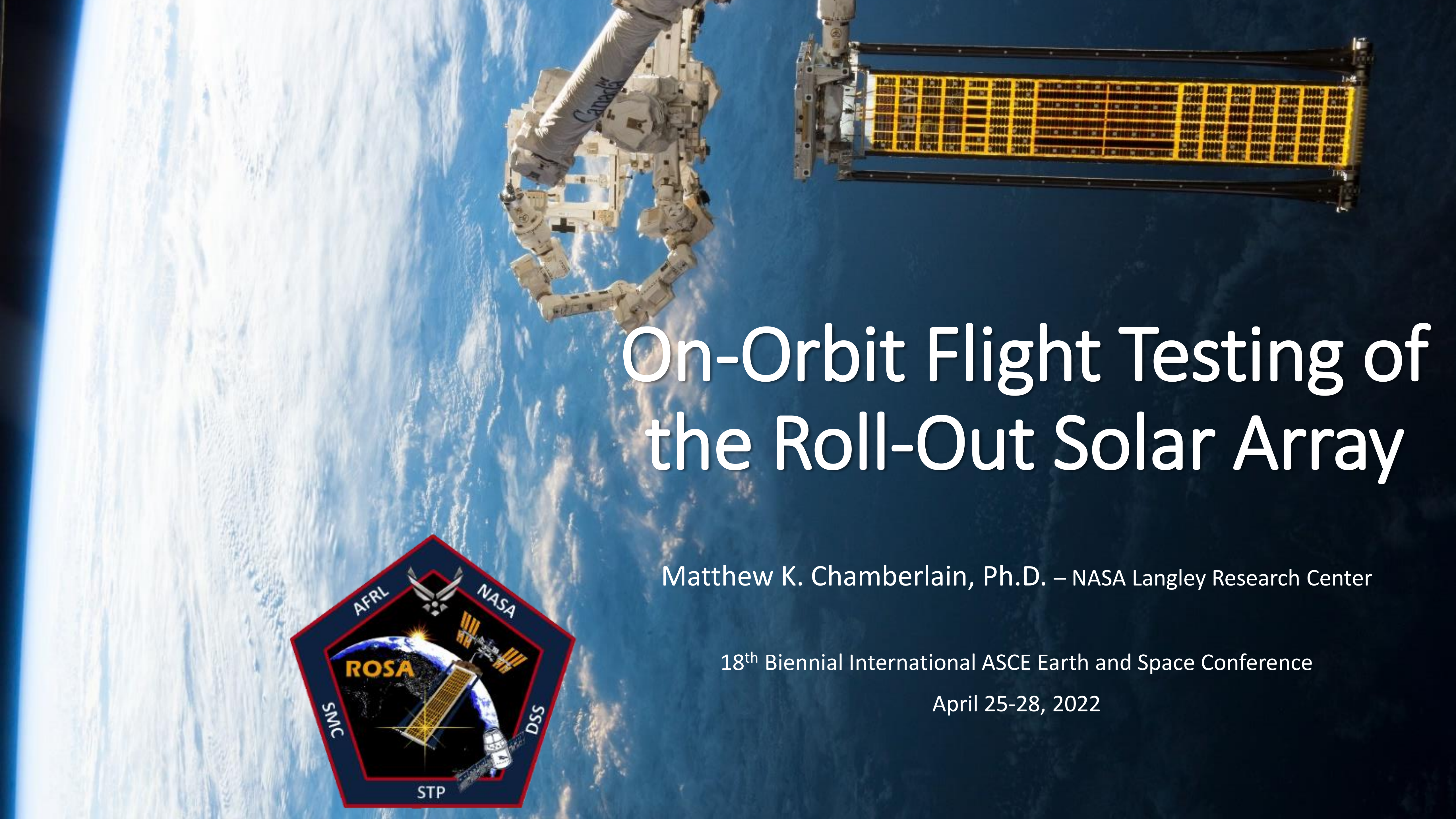


On-Orbit Flight Testing of the Roll-Out Solar Array

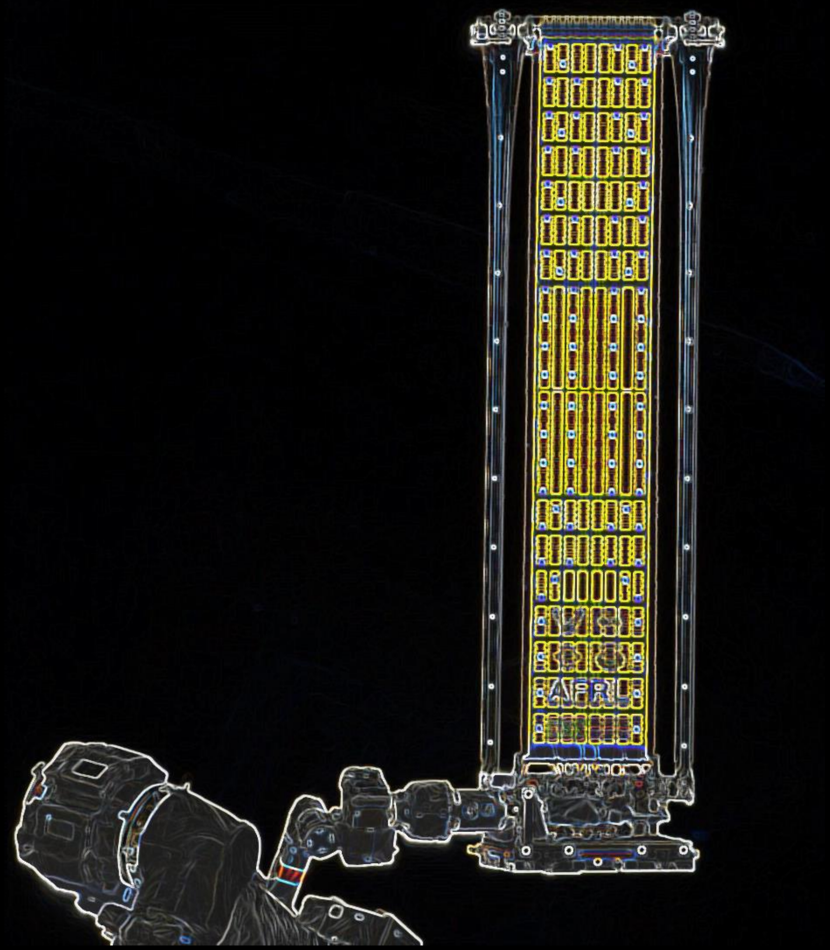
Matthew K. Chamberlain, Ph.D. – NASA Langley Research Center

18th Biennial International ASCE Earth and Space Conference

April 25-28, 2022

Outline

- Background on ROSA and its Development
- Flight Experiment
  - Timeline
  - Instrumentation
  - Test Plan
- Experimental Results
  - Accelerometer
- Processing of Photogrammetry Data
- Photogrammetry Results
- Discussion and Future Work



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Biography

Matthew K. Chamberlain

Head, Structural Dynamics Branch

NASA Langley Research Center

- Research Interests:
  - Lightweight deployable spacecraft structures
  - Novel experimentational methods
  - Nonlinear finite element analysis
- Education:
  - BS, Mechanical Engineering, Carnegie Mellon University
  - MS, Mechanical Engineering, Georgia Institute of Technology
  - Ph.D., Mechanical Engineering, Georgia Institute of Technology

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The Case for Lightweight Solar Arrays

- Any weight or volume saved in spacecraft is valuable
- State of the art for satellite solar arrays: heavy rigid deployable panels
- NASA and DoD are interested in lighter, smaller arrays:
  - Satellites
  - Deep space solar electric propulsion
  - Lunar surface power
- ROSA is an inexpensive, rollable solar array concept that is lighter and takes up a fraction of the stowage space of a standard rigid solar array
- Other lightweight competitors:
  - Northrup Grumman Ultraflex arrays
  - Lockheed Martin Multi-mission Modular Solar Array

Juno solar panels (typical for rigid arrays)

Ultraflex arrays on Cygnus

LM MMSA

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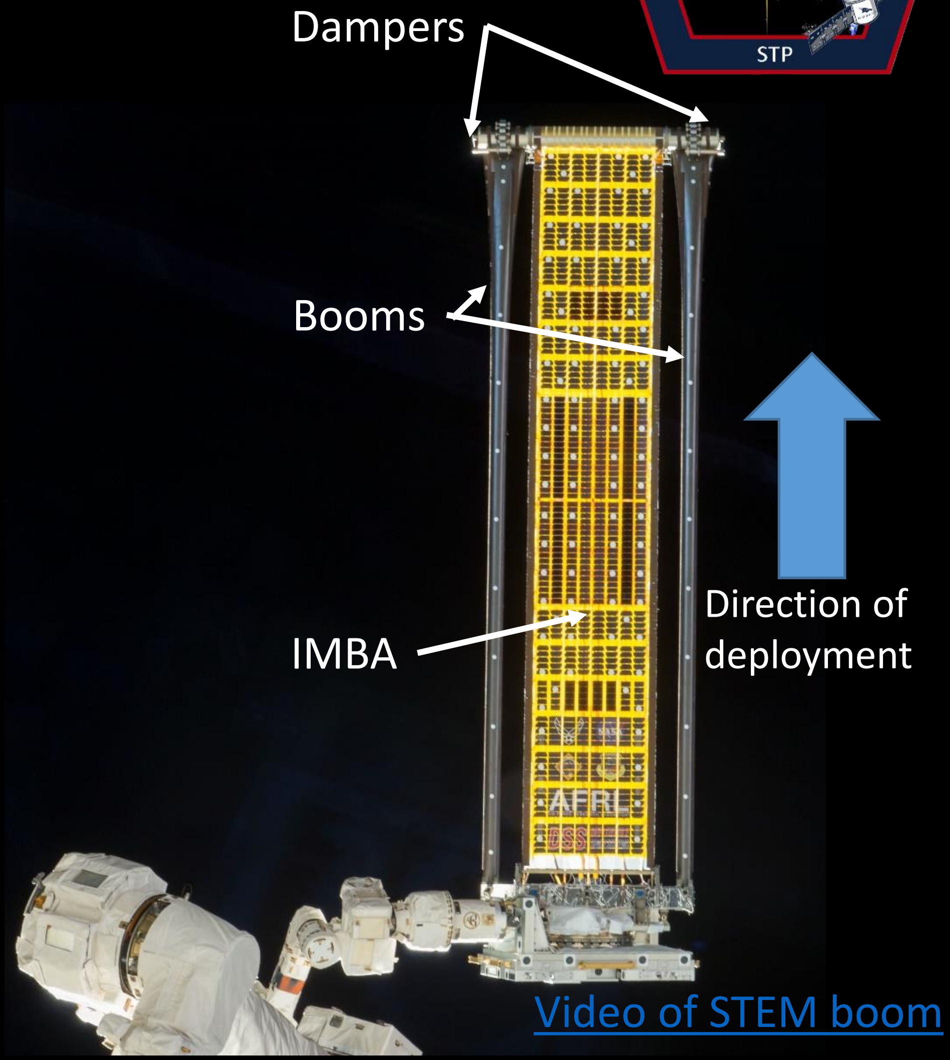
The Roll-Our Solar Array

- Lightweight strain-energy driven deployable solar array
- Common but insufficient analogies:
  - Party favor
  - Slap bracelet
  - Tape measure
- Design overview
  - High-strain composite slit tube booms
  - Integrated Modular Blanket Assembly (IMBA or "blanket") made up of lightweight photovoltaics attached to mesh substrate
  - Booms and IMBA roll up on mandrel for launch
  - No motors required for deployment (strain energy used exclusively)
  - Dampers control rate of deployment



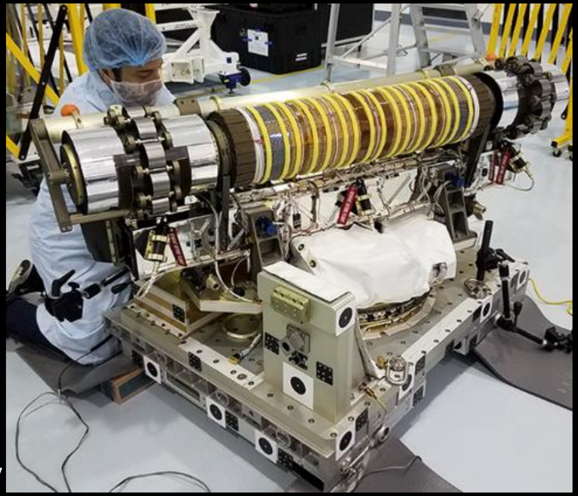
[Video of STEM boom]

Development of ROSA

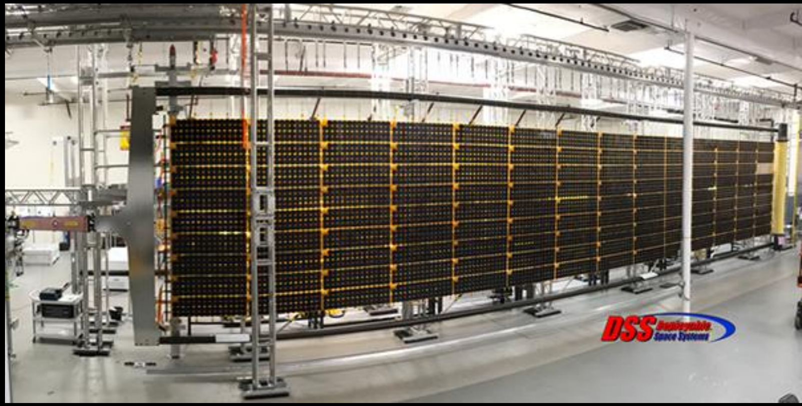
- Developed by Deployable Space Systems incrementally over last 10 years
  - AFRL SBIRs
  - NASA (Langley, Glenn, JSC) SBIRs
  - STMD Solar Array Structures program (2012 to 2015)
- AFRL flight experiment (2017)
  - Air Force Research Laboratory (AFRL) project supported by Department of Defense Space Test Program (STP) and NASA
  - ROSA scaled to fit in Dragon trunk (5.4 m long, 1.67 m wide)
  - 4 inch diameter 3-ply carbon fiber reinforced epoxy booms
  - Designed to retract, unlike most ROSA arrays

20 kW ROSA Wing (2014)

ISS Flight Experiment ROSA (2017)



Why Flight Test?



- First large-scale use of high strain composites in space
    - Concerns about relaxation
    - Survivability after rolling, storage, launch, and deployment
- Ground testing of lightweight deployable structures is a challenging
    - Offloading necessary
    - Damping hard to measure

- Primary Goal: Demonstrate strain energy deployment of solar array
- Secondary Goals:
    - Characterize deployment loads and kinematics
    - Characterize deployed structural dynamics
        - Driven dynamics
        - Eclipse dynamics
        - Damping
    - Evaluate performance of solar cells after rolling, storage, launch, and deployment
    - Characterize retraction loads and kinematics

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ROSA Flight Experiment Overview

Launch from KSC

June 3, 2017

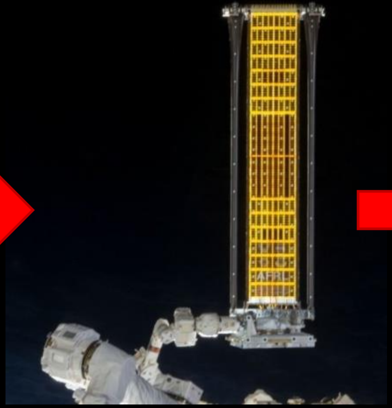
Extraction from Dragon Trunk

June 17, 2017

Positioned for Deployment

June 17, 2017

Deployment Complete



June 18, 2017

Jettison

June 26, 2017

- 7-Day window for all experiments

<u>Day 0:</u>
- Deployment
- First sine sweeps

<u>Day 1-4:</u>
- Structural dynamics experiments
- Eclipse dynamics

<u>Day 5:</u>
- Repositioning
- Photovoltaic experiments

<u>Day 6:</u>
- Attempted retraction

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Deployment: June 18th, 2017 (sped up ~20x)

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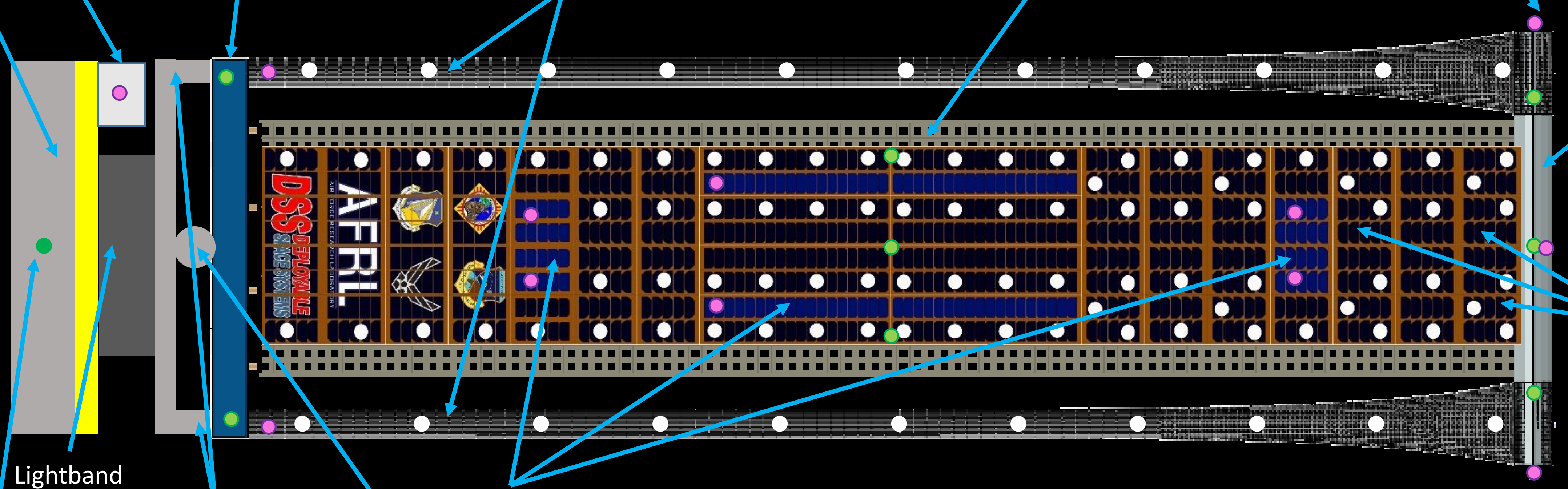
Experimentation on ISS

Goal	Measurement	Instrumentation
1. Characterize deployment loads and kinematics	• Damper voltage and current • Array displacements • Environmental conditions	• Damper readings • RTDs • Accelerometers • Photogrammetry
2. Characterize deployed structural dynamics	• Array displacements • Environmental conditions	• RTDs • Accelerometers • Photogrammetry
3. Evaluate performance of solar cells	• Solar cell string voltage • Solar cell string current • Environmental conditions	• RTDs • DAS
4. Characterize retraction loads and kinematics	• Damper voltage and current • Array displacements • Environmental conditions	• Damper readings • Damper temperatures • Photogrammetry

ROSA Deployed Configuration and Instrumentation

Direction of Deployment



- Accelerometers
- Photogrammetry Targets
- Resistance Temperature Detectors (RTDs)

Cameras (Not Shown):
- 4 on ROSA root structure
- 2 on SPDM
- Various on ISS (HD and SD)

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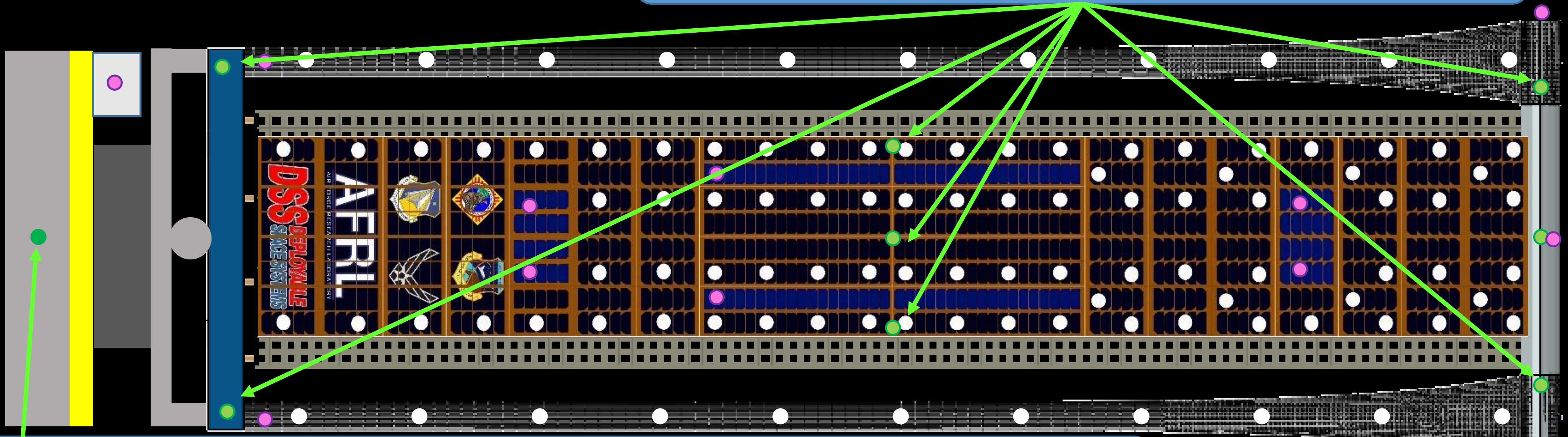
Accelerometers

<u>8x Unidirectional Accelerometers</u>

- Silicone Designs capacitive micromachined sensors
- ±5 g range
- Chosen for low noise, low mass, operating temperature range, shock rating, and spaceflight heritage
- Positioned to best capture first structure and blanket modes



<u>1x Triaxial Accelerometer</u>

- Silicone Designs capacitive micromachined sensor
- ±10 g range
- Chosen for low noise, operating temperature range, shock rating, and spaceflight heritage
- Positioned to capture any base motion
- ***Damaged in handling prior to launch***

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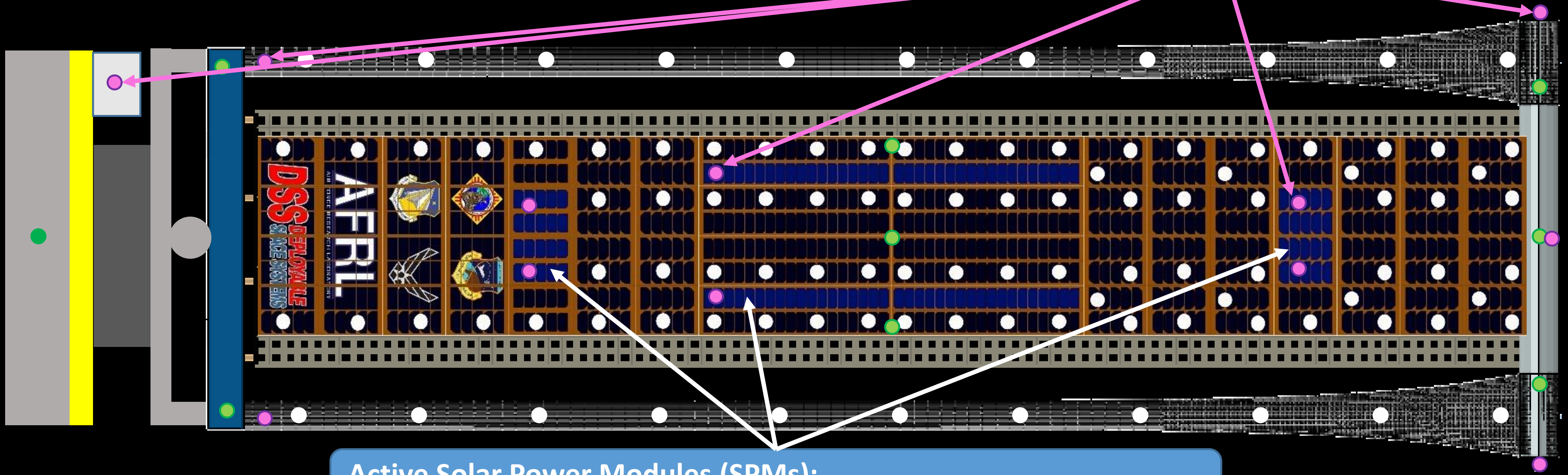
Other Instrumentation

Resistance Temperature Dectectors (RTD)
- BF Goodrich Rosemount Aerospace
- Spaceflight heritage on solar arrays
- 6x on SPM
- 2x on dampers
- 1x on DAS



Active Solar Power Modules (SPMs):
- SolAero, Northrup Grumman, Spectrolab (left to right)
- Mass simulators surrounding to match each SPM
- IV sweeps carried out one string at a time in 10 minute segments to verify functionality, compare with ground tests

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Camera Support

- 4x Ecliptic cameras on ROSA experiment
  - Narrow fields of view
  - Assigned to specific hardware to verify function
  - Static
- 2x SPDM cameras
  - Can be moved, zoomed
- ISS Cameras
  - Various types, resolutions, ages
  - CP3 and CP13 used for photogrammetry
- Handheld Cameras
  - Operated by astronauts
  - Used for glamour shots

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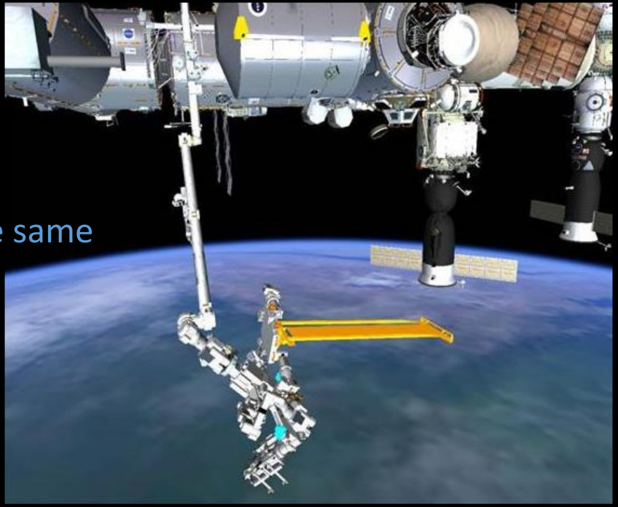
Pre-Flight Camera Analysis

- Precise position of robot arm with ROSA determined by JSC prior to flight based on
  - Lighting/Shadows
  - Optimal view of photogrammetry targets
  - Best angles for direct illumination for IV sweeps

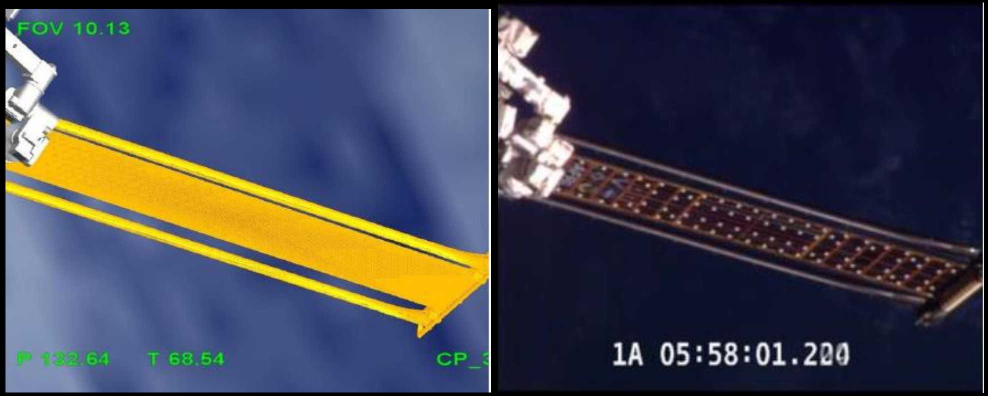
  Not necessarily the same
- Flight hardware surveyed prior to launch
- Photogrammetry model built prior to launch based on ISS camera positions and characteristics
- Extensive photographs of hardware taken
- Pre-flight imagery from onboard cameras saved
- Targets utilized:
  - 2 in white circles provided by JSC (flight heritage)
  - Orange balls on dampers
  - Silver marker on booms

  Did not work

Preflight simulated ROSA



Simulated vs actual camera view



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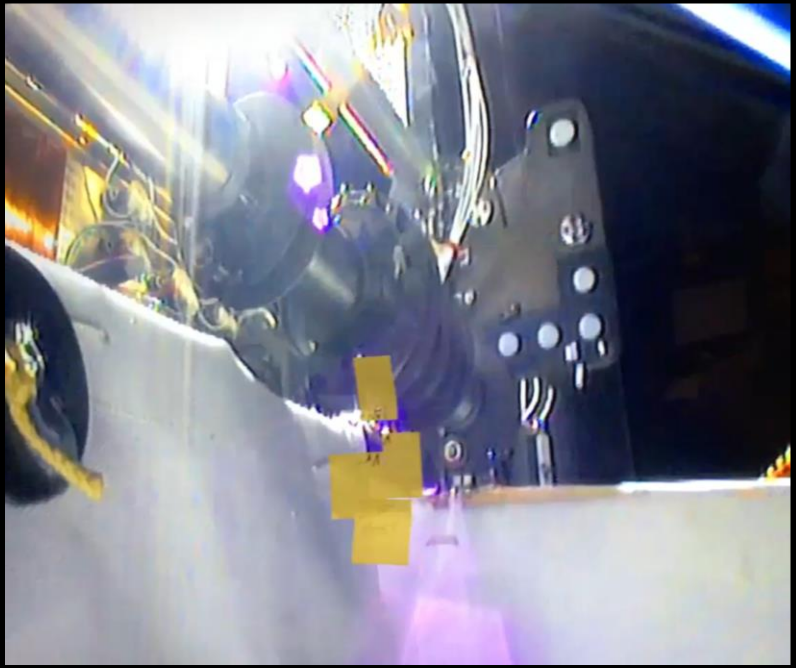
Dynamics Test Plan

- Driven motion:
  - Drive base with sinusoidal out-of-plane motion of ±0.5 in
  - Sweep through expected frequency ranges of structural modes
  - Carry out 5x each night and day “science” runs around measured modes
  - Identify any trends in dynamics (time/temp dependency)
  - Total of 30 experiments → Became more than 90
- Eclipse dynamics:
  - Record accelerometer data for a few minutes around eclipse entry or exit
  - Repeat 5x each



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Typical Dynamics Test Run

- Send desired test parameters to ROBO in MCC
  - Test duration
  - Start and end frequency
  - Amplitude
- Camera views selected
- Conditions for test checked
  - Lighting and shadows for photogrammetry
  - Temperature
  - Time left in day/night cycle
  - Any predicted LOS
- ROBO sends commands through robot arm to ROSA
- Data collection begins just before test run, ends just after
- Data downlinked at 20 Hz, saved at 200 Hz:
  - Accelerations
  - Temperatures
  - Motor statuses, settings, voltages, currents, etc
- ***Settings for next test often pre-arranged but sometimes adjusted based on real-time analysis***

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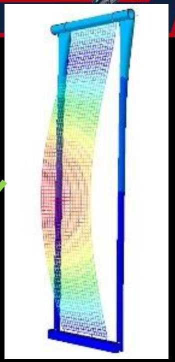
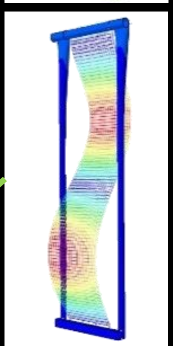
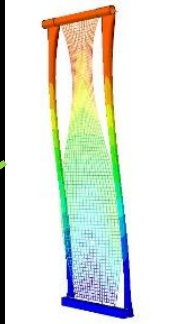
Structural Dynamics Results

Pre-Flight Modal Predictions

Shell-Based Blanket Model (ANSYS)			**Truss-Based Blanket Model (Abaqus)**		
Mode	**Frequency (Hz)**	**Shape**	**Mode**	**Frequency (Hz)**	**Shape**
1	0.54	Structural Bending	Planned Test #1	0.50	Structural Bending
2	0.66	Structural Torsion	2	0.64	Structural Torsion
3	0.91	Blanket Torsion	4	1.24	Blanket Torsion
4	0.93	Blanket Saddle	Planned Test #2		
5	0.94	Blanket Drum	3	0.98	Blanket Drum
6	1.12	2nd Order Lateral Blanket Drum			
7	1.49	3rd Order Lateral Blanket Drum			
8	1.78	2nd Order Blanket Twist			
9	1.79	2nd Order Blanket Drum	5	1.88	2nd Order Blanket Drum
10	1.82	2nd Order Blanket Saddle	Planned Test #3		
11	1.87	Lead-Lag in Plane			
12	2.00	3rd Order Blanket Twist			
13	2.06	4th Order Lateral Blanket Drum	6	2.22	Lead-Lag in Plane







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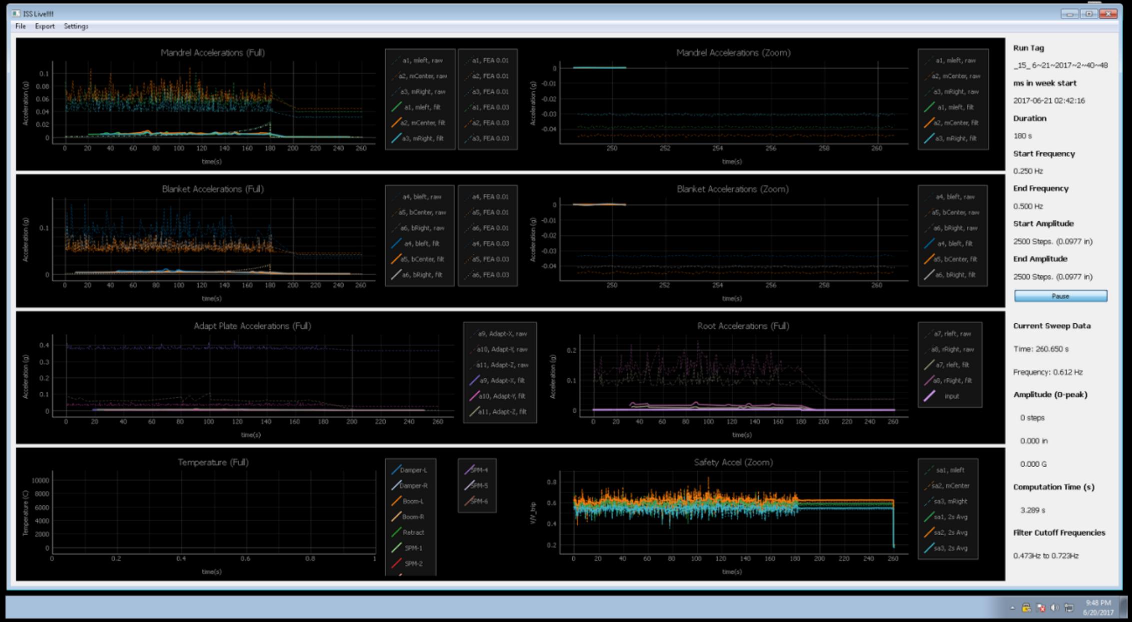
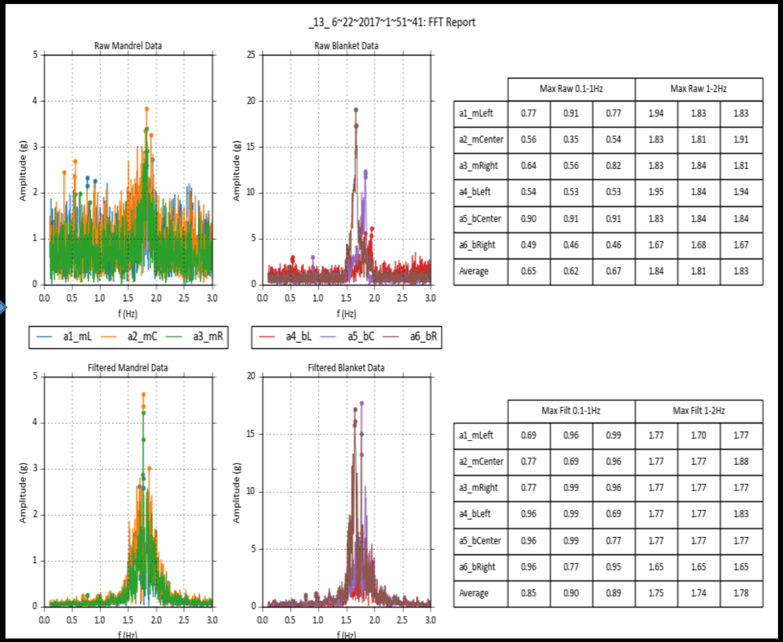
Real-Time Analysis

Real-Time GUI Output for Experimental Run



Post-Run Quick Report



	Max Raw 0.1-1Hz			Max Raw 1-2Hz		
a1_mLeft	0.77	0.91	0.77	1.94	1.83	1.83
a2_mCenter	0.56	0.35	0.54	1.83	1.81	1.91
a3_mRight	0.64	0.56	0.82	1.83	1.84	1.81
a4_bLeft	0.54	0.53	0.53	1.95	1.84	1.94
a5_bCenter	0.90	0.91	0.91	1.83	1.84	1.84
a6_bRight	0.49	0.46	0.46	1.67	1.68	1.67
Average	0.65	0.62	0.67	1.84	1.81	1.83

	Max Filt 0.1-1Hz			Max Filt 1-2Hz		
a1_mLeft	0.69	0.96	0.99	1.77	1.70	1.77
a2_mCenter	0.77	0.69	0.96	1.77	1.77	1.88
a3_mRight	0.77	0.99	0.96	1.77	1.77	1.77
a4_bLeft	0.96	0.99	0.69	1.77	1.77	1.83
a5_bCenter	0.96	0.99	0.77	1.77	1.77	1.77
a6_bRight	0.96	0.77	0.95	1.65	1.65	1.65
Average	0.85	0.90	0.89	1.75	1.74	1.78

- Data from accelerometers, RTDs recorded on ISS at 200 Hz (during excitation and for ~ 2 min afterward)
- Data downlinked in real-time at 20 Hz for quick-look analysis
- Run parameters for next experiment adjusted on the fly
- Imagery recorded for select runs with good lighting
- All data for select runs downloaded later at original sampling rate (lots of parsing followed)

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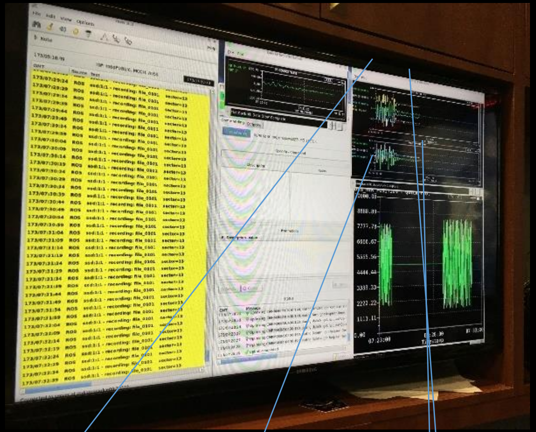
Unexpected Dynamics

Low 1st Bending Mode

- First structural mode hard to excite, appeared highly damped
- Evidence from video, robot arm joint sensors indicates arm and FRAM were moving
- May have been result of structural interaction between ROSA and ISS robot arm

ROBO Console



SPDM Joint Moment Feedback

Right Edge Flap

- Blanket exhibited un-symmetric behavior
- Right edge consistently moved independently around 0.6 – 0.7 Hz
- Left and center accelerometers showed other independent modes
- Caused by uneven tensioning of blanket? Failure of one tension spring?

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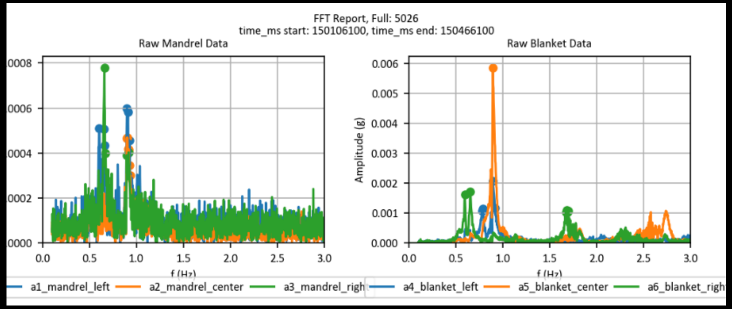
Overview of Post-flight Analyses

- Huge quantities of accelerometer data processed
  - 90+ runs recorded at 200 Hz
  - All data downlinked in <u>real time</u> at 20 Hz
  - 60+ select <u>full</u> data sets downloaded <u>later</u> for analysis
- Video recorded for photogrammetry analysis for key experimental runs

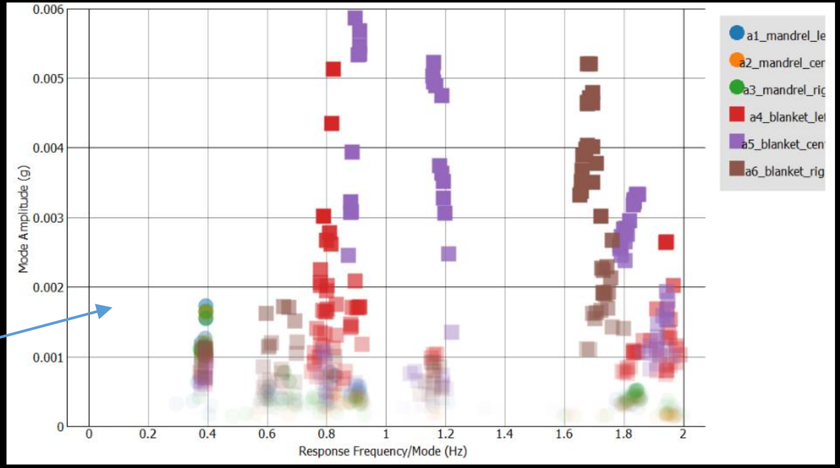
- Post-Flight Goals:
  - Identify ROSA frequencies and mode shapes below 2 Hz
  - Calculate structural damping
  - Reconstruct mode shapes

- **<u>Plotting</u>** used extensively to help identify trends
- Excitation and free-decay data analyzed separately
- Photogrammetry analysis carried out on 4 runs

FFTs of filtered accelerometer data for one run



Conglomeration of FFT peaks from all runs



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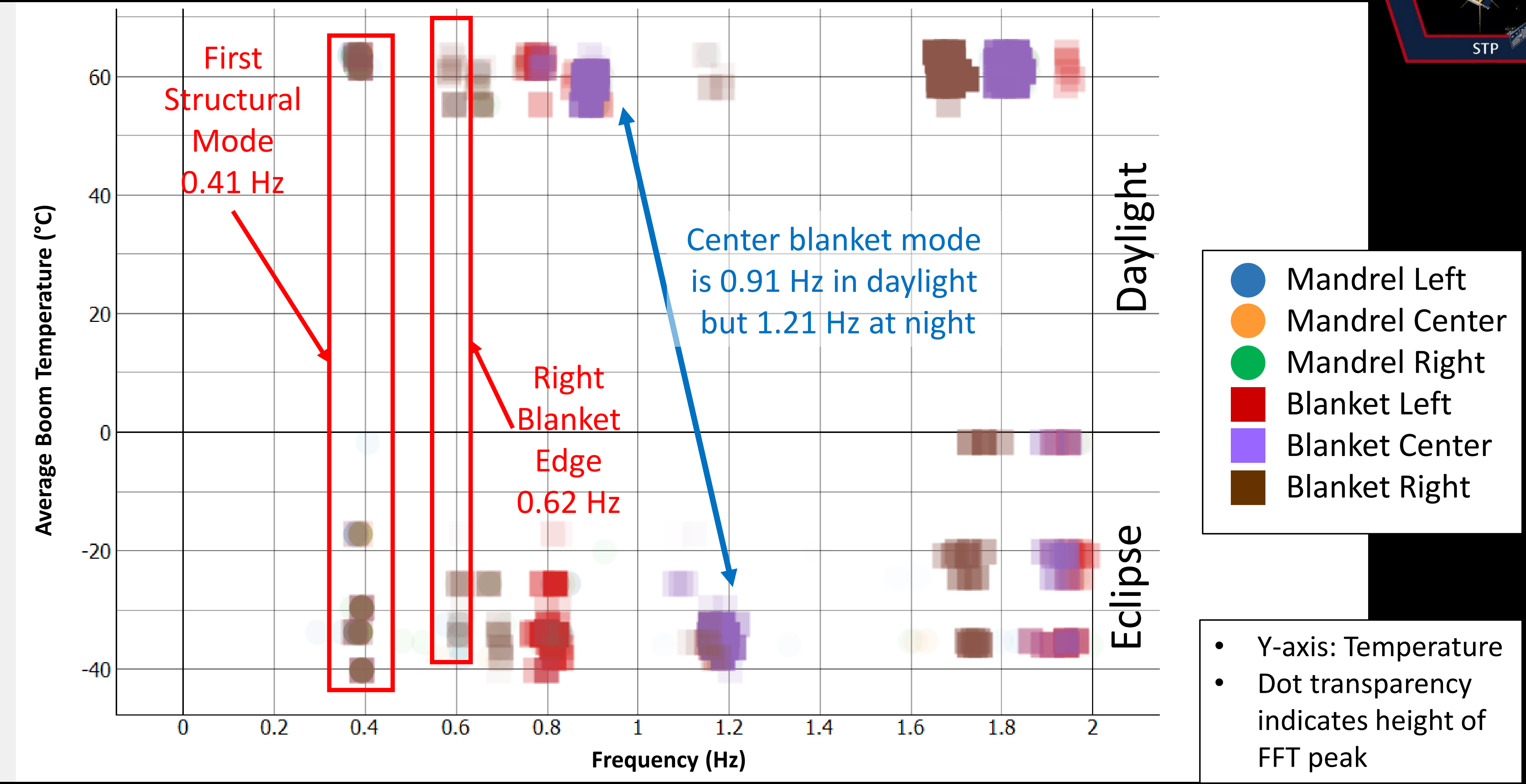
Structural Modes in Accelerometer Data



- Y-axis: Temperature
- Dot transparency indicates height of FFT peak

Results from Previous Analyses

Mode	Average FEM Predicted Frequency (Hz)	Average Measured Frequency (Hz)	Estimated Damping (%)	Shape
1	0.52	0.40	3.5	Structural bending
2	0.65	0.62	3.9	Structural torsion
3	*	0.68	1.6	Blanket right edge w/ torsion
4	*	0.81	1.7	Blanket left edge and center
5	0.93 **	0.91	0.8	Blanket saddle
6		1.21	1.5	Blanket saddle
7	*	1.70	0.7	Blanket right edge
8	*	1.77	1.0	Blanket right edge

* Indicates a mode shape spoiled by uneven blanket tension

** Saddle mode appears at different frequencies between day and night

Takeaways:

- *Unanticipated situations spoiled preflight FEM predictions:*
  - *Low 1^{st} bending mode*
  - *Loose right edge*
- *Good FEM prediction of first blanket mode*
- *Higher damping on 1^{st} and 2^{nd} modes*

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Photogrammetry Cases

- Four experimental runs based on:
  - Largest recorded acceleration responses at modes of interest below 2 Hz
  - Coverage of all modes of interest identified previously
- Processed by separate teams at NASA Langley and NASA Johnson
  - Labor-intensive process
  - JSC team only completed 2 out of 4 cases in time for publication
- Data delivered as location time histories for targets (converted to displacements and band-pass filtered)

Run Number	Lighting	Start Frequency (Hz)	End Frequency (Hz)	Duration (s)	Rational for Selection	Processed by JSC?	Processed by LaRC?
5026	Day	0.50	1.25	300	• High right blanket response at ~ 0.6 Hz • High right blanket response at ~ 0.65 Hz • High center blanket response at ~ 0.9 Hz	✓	✓
5052	Night	0.50	1.25	300	• High left blanket response at ~ 0.82 Hz • High center blanket response at ~ 1.16 Hz • Is 1.16 Hz mode a shifted day mode?		✓
5074	Day	1.50	2.00	300	• High right blanket response at ~ 1.68 Hz • High center blanket response at ~ 1.84 Hz	✓	✓
5080	Day	0.37	0.41	180	• High mandrel response at ~ 0.39 Hz		✓

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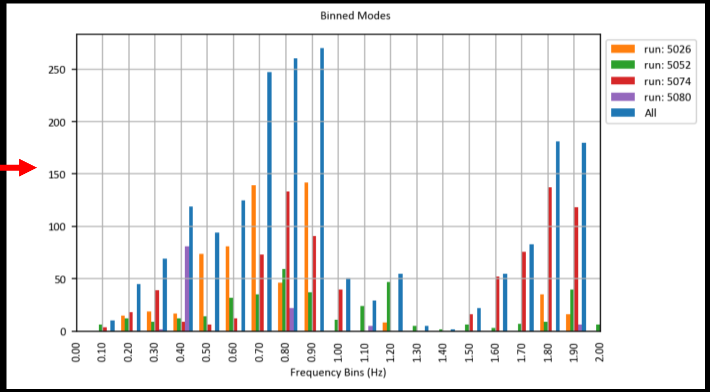
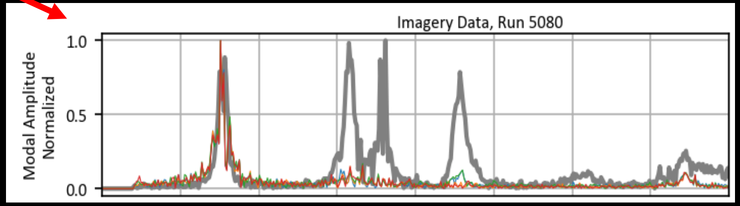
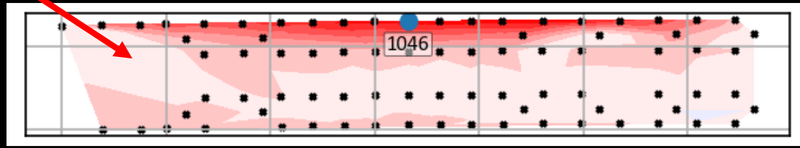
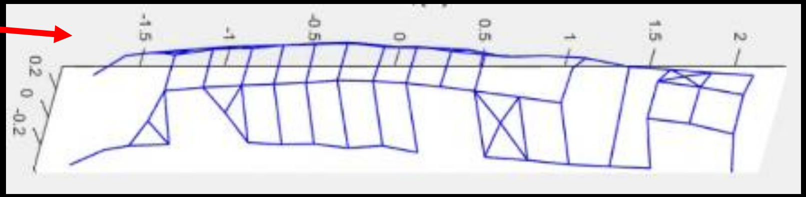
Analysis Methods

- FFTs calculated for time histories of all target displacements to assess frequency content for all runs
  - Significant peaks counted by 0.1 Hz bins to identify active frequencies for each run
  - FFTs for targets nearest to accelerometers compared with acceleration FFTs analyzed previously
- Contour plots created by normalizing displacements for a certain time point at which a target of interest is maximized
- Eigenvalue Realization Algorithm utilized to reconstruct system modes and mode shapes









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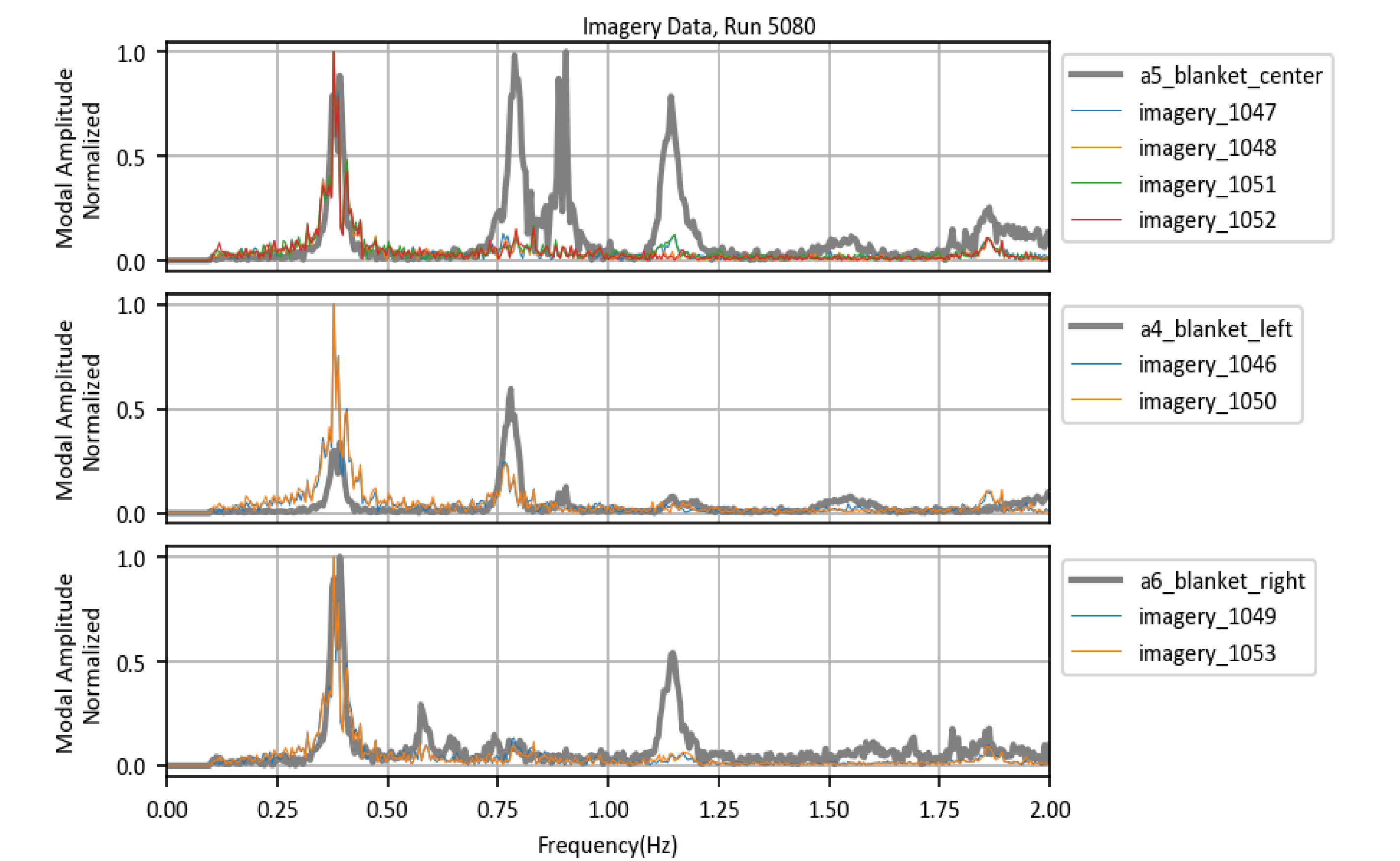
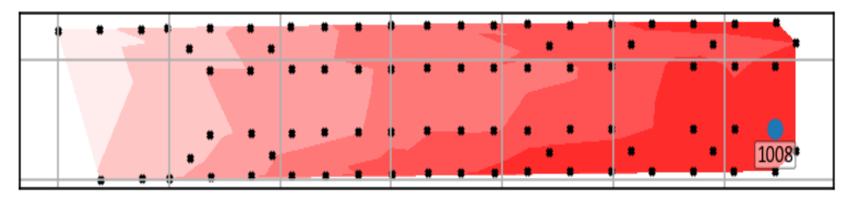
Analysis of Run 5080

Comparison of Accelerometer and Nearby Photogrammetry Target FFTs

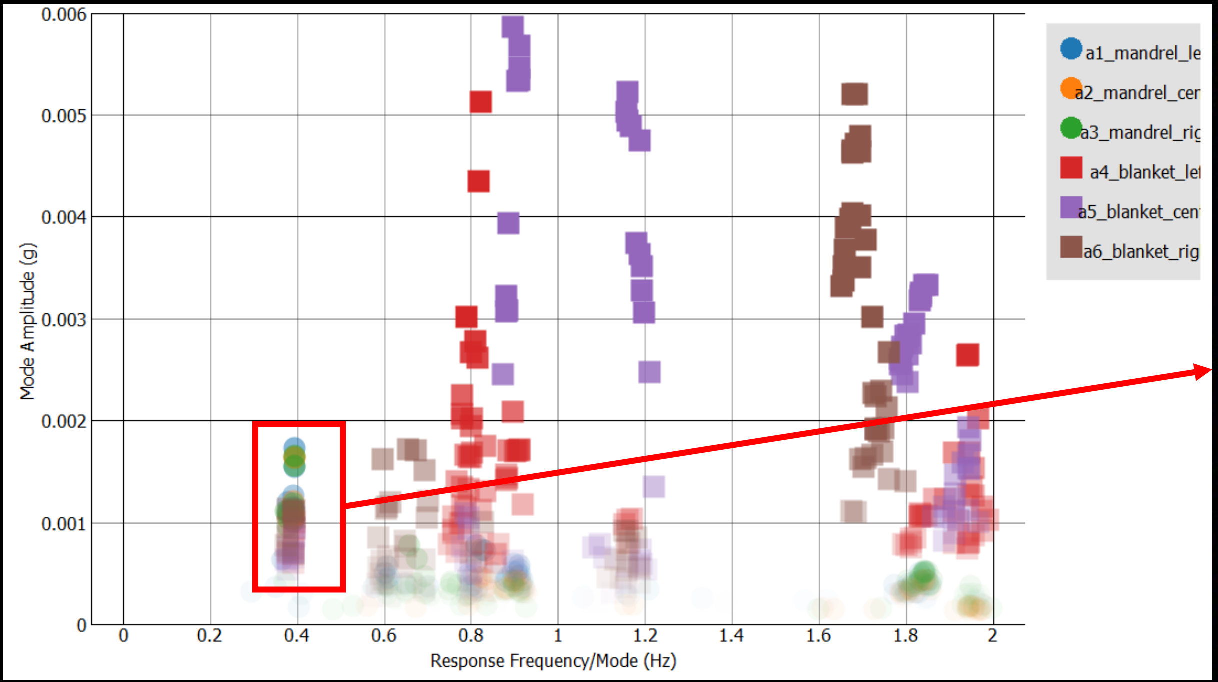


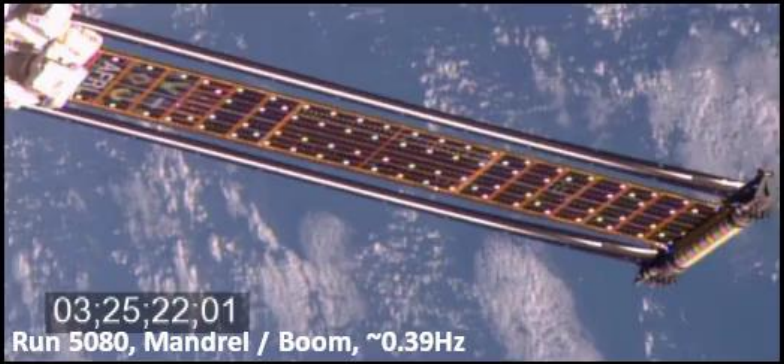
- Narrow-band sine sweep around first structural mode

Contour for 0.39 Hz Mode from Run 5080

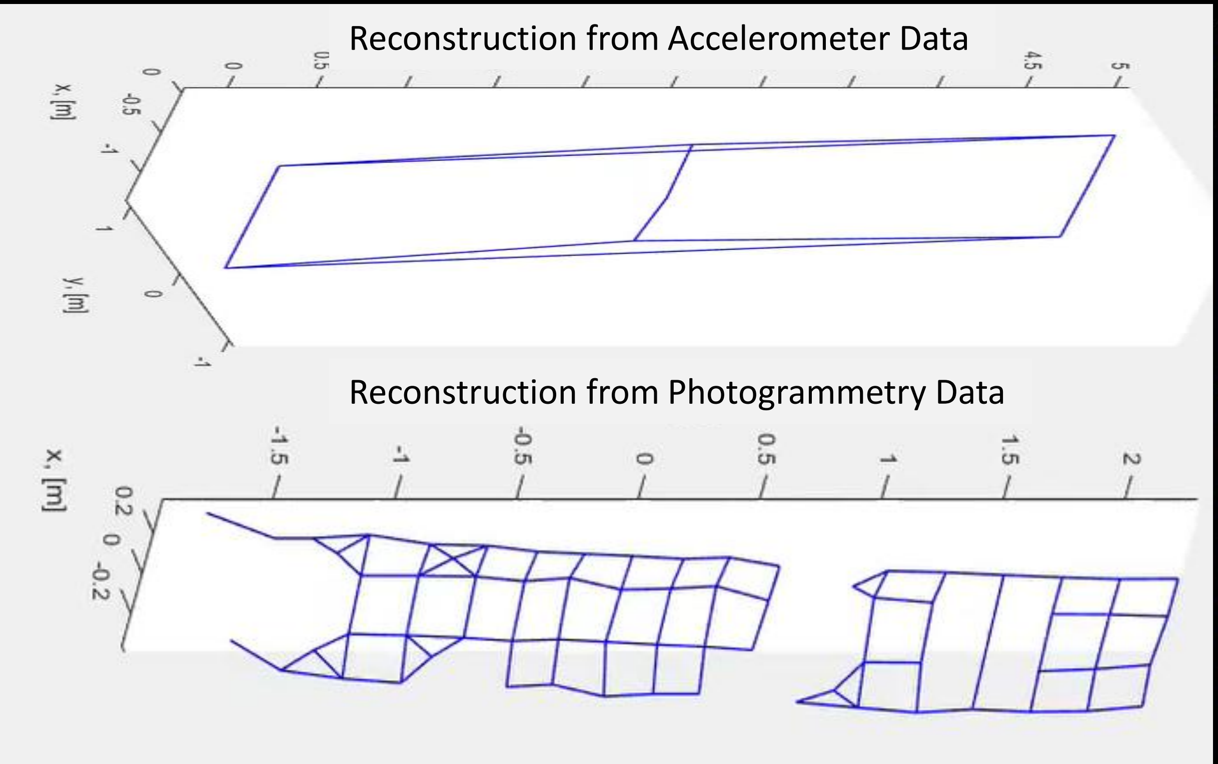


Hunting for the First Bending Mode



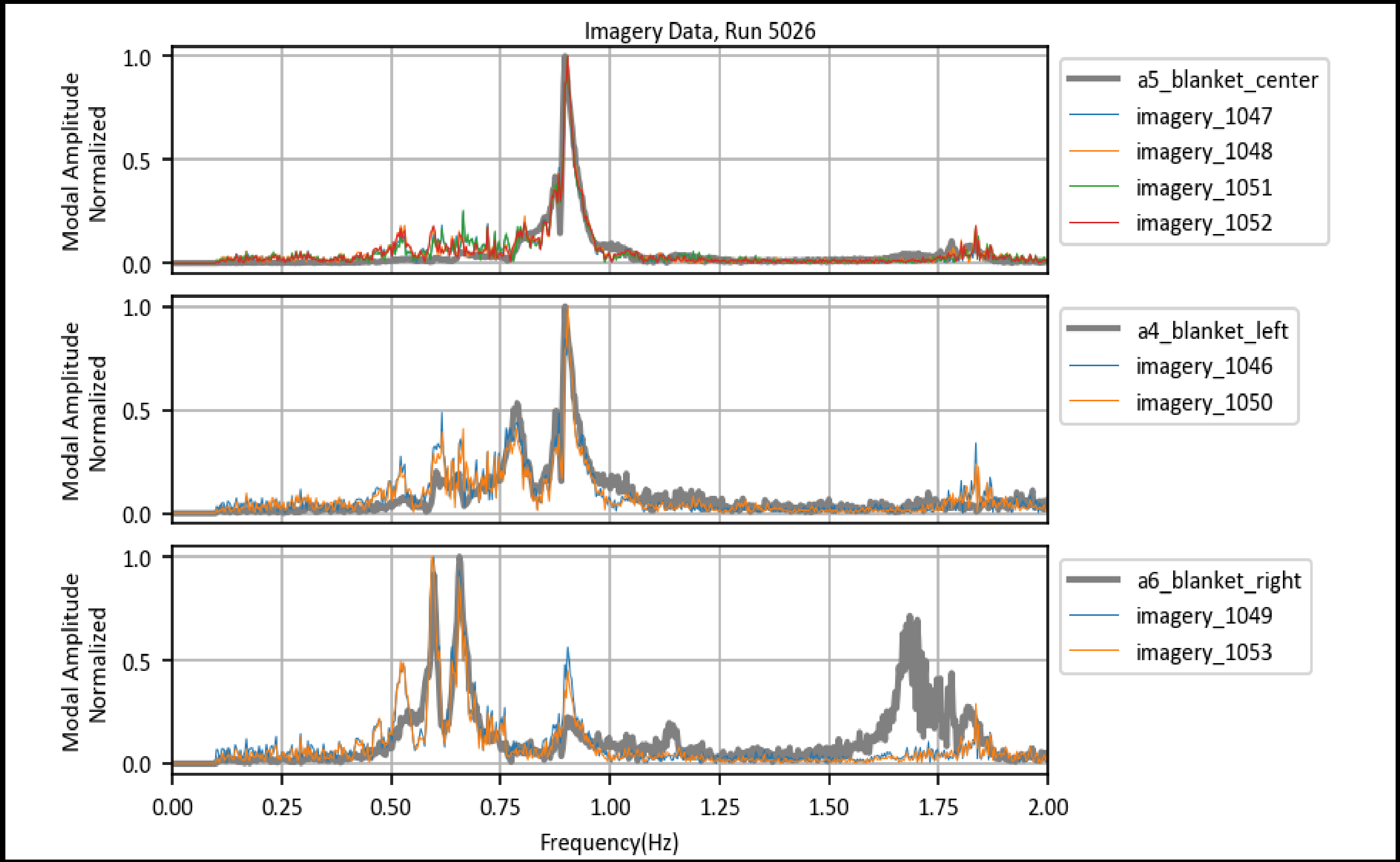


Reconstructed
0.39 Hz Daylight First Bending Mode



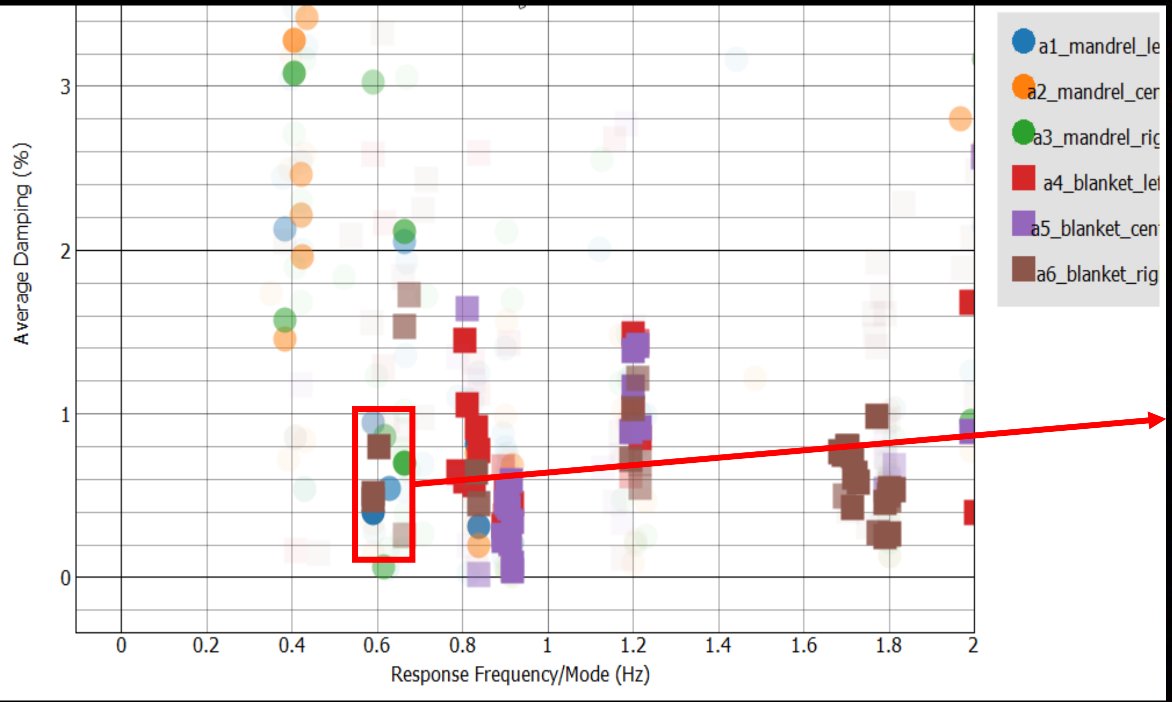
Analysis of Run 5026

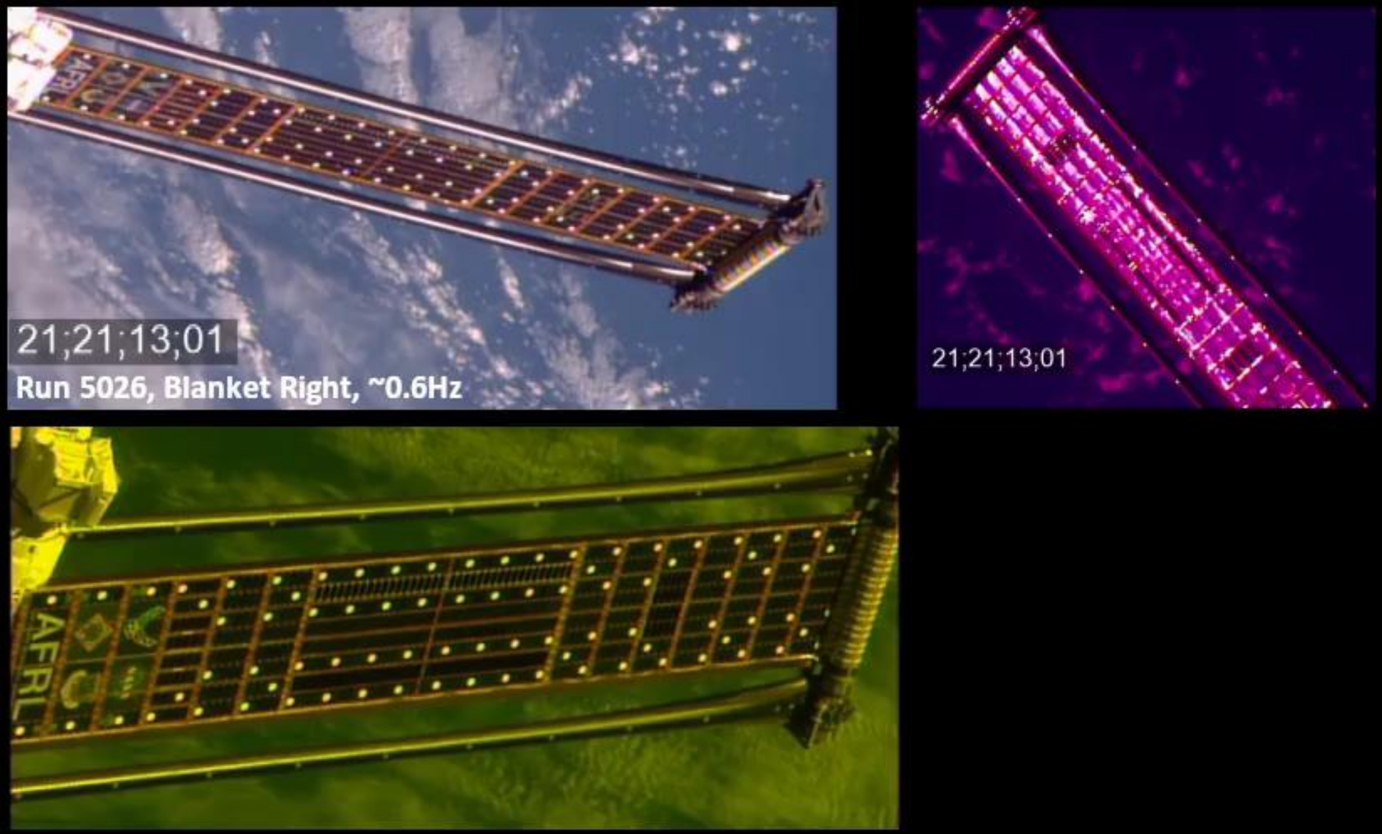
Comparison of Accelerometer and Nearby Photogrammetry Target FFTs



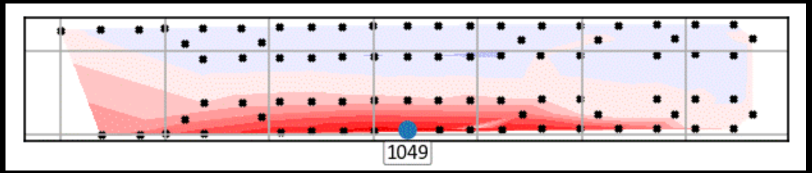
- Low-frequency daytime blanket run
- Several large responses in accelerometer data are examined further here:
  - 0.61 Hz
  - 0.91 Hz

Right Blanket Edge Mode at 0.60 Hz





Contour for 0.61 Hz Mode from Run 5026



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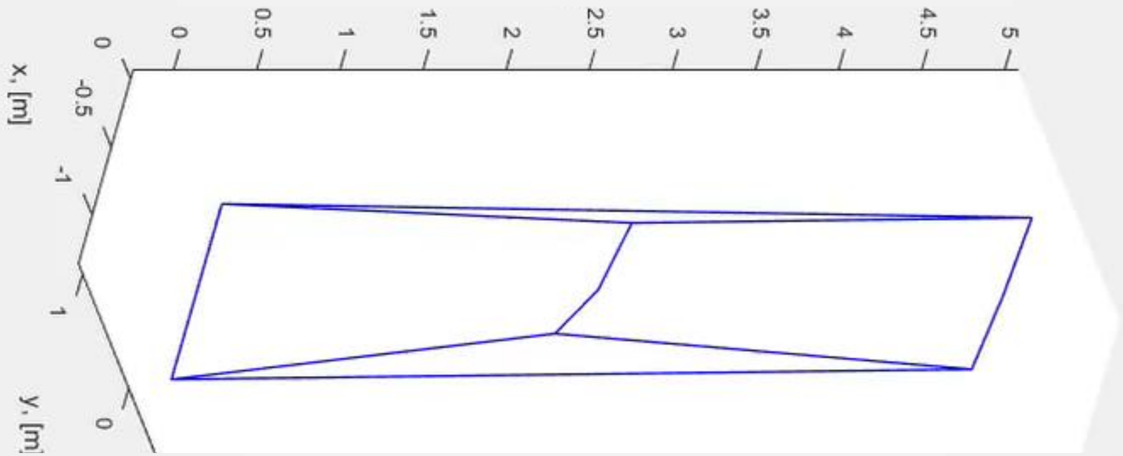
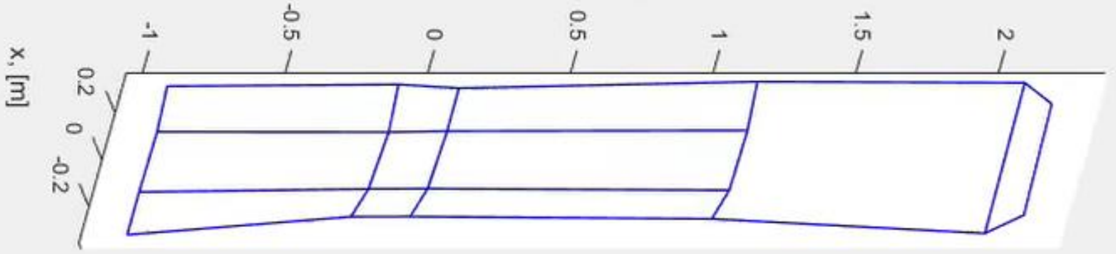
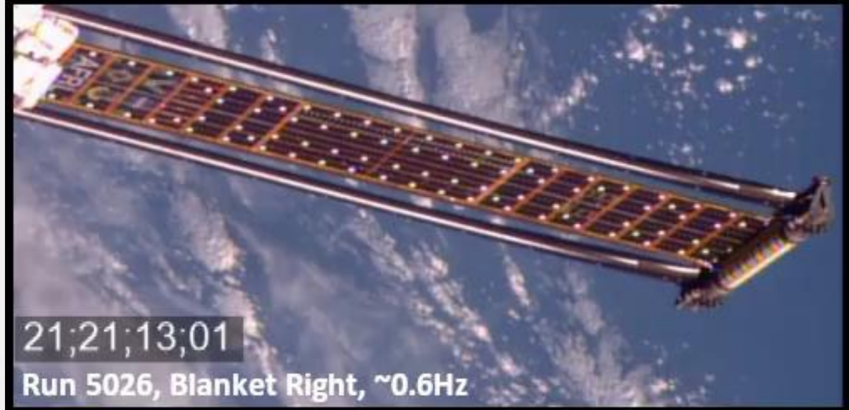
Reconstructed
Right Blanket Edge Mode at 0.60 Hz

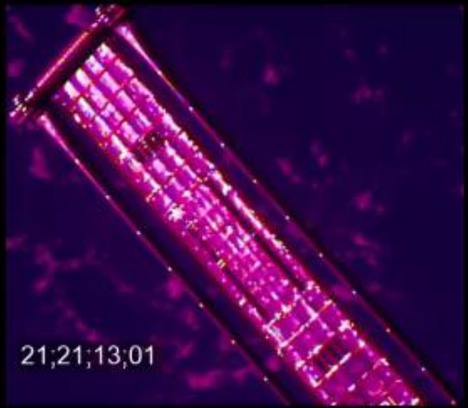
Reconstruction from Accelerometer Data (run 5044)



Reconstruction from Photogrammetry Data







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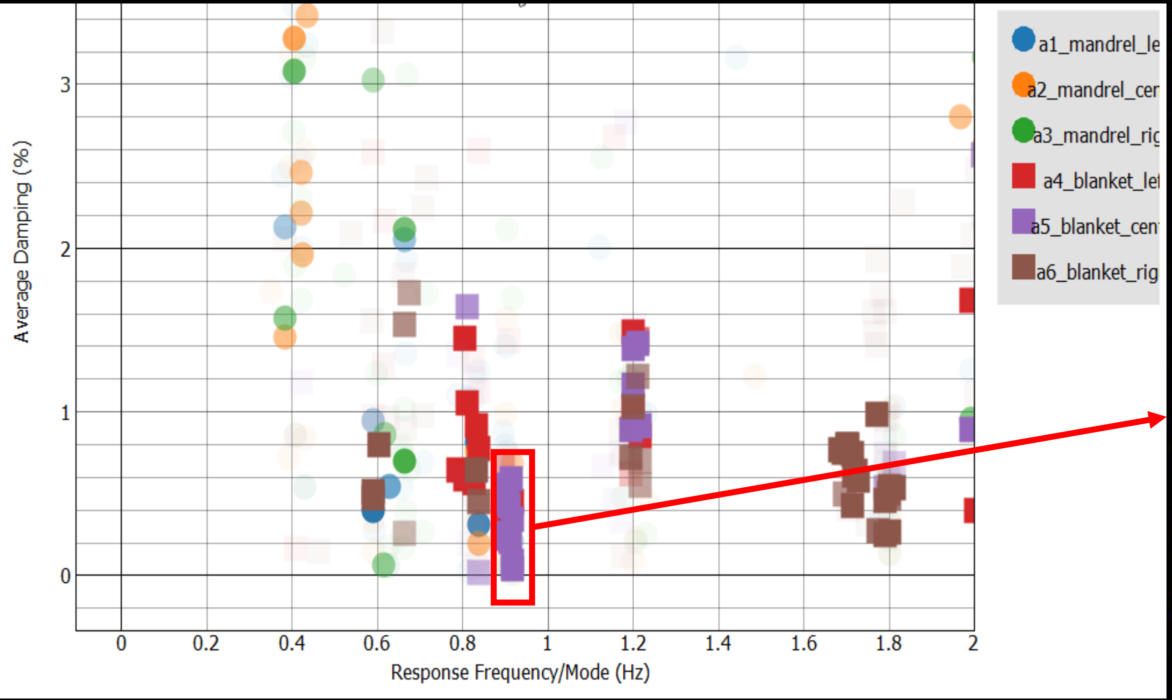
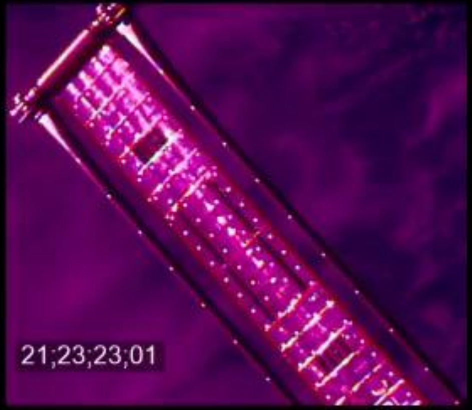
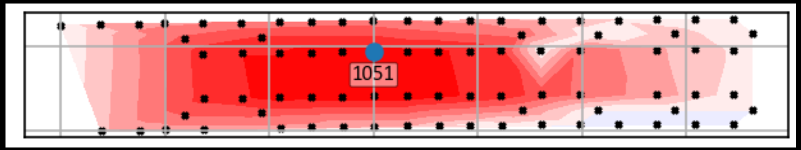
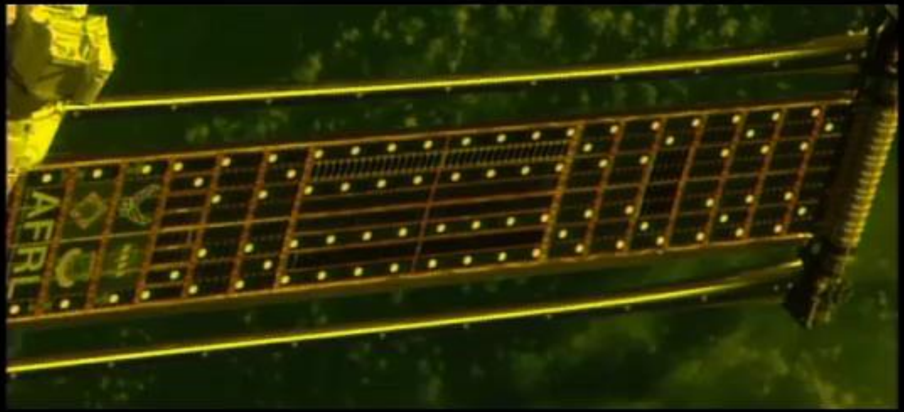
Day-Only Blanket Mode at 0.91 Hz





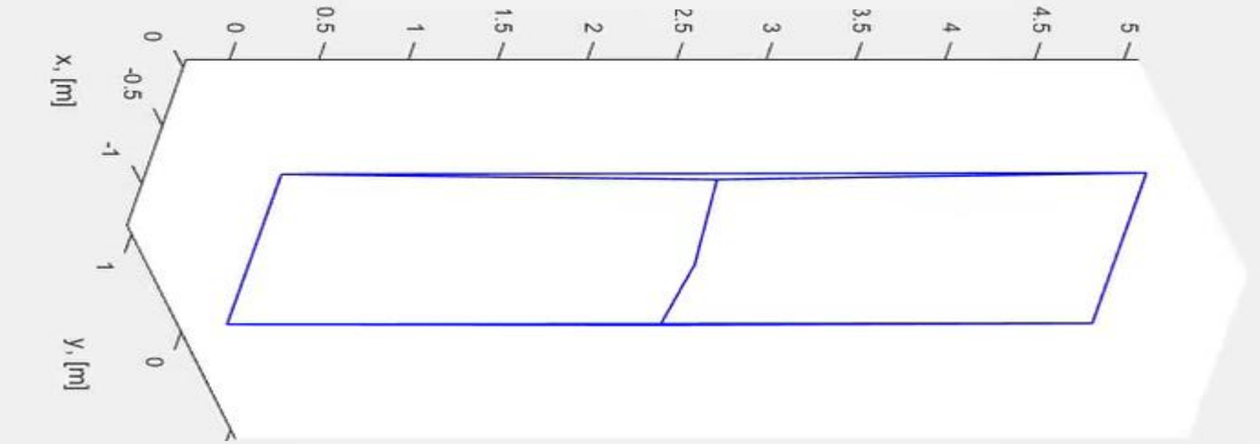
Contour for 0.89 Hz Mode from Run 5026



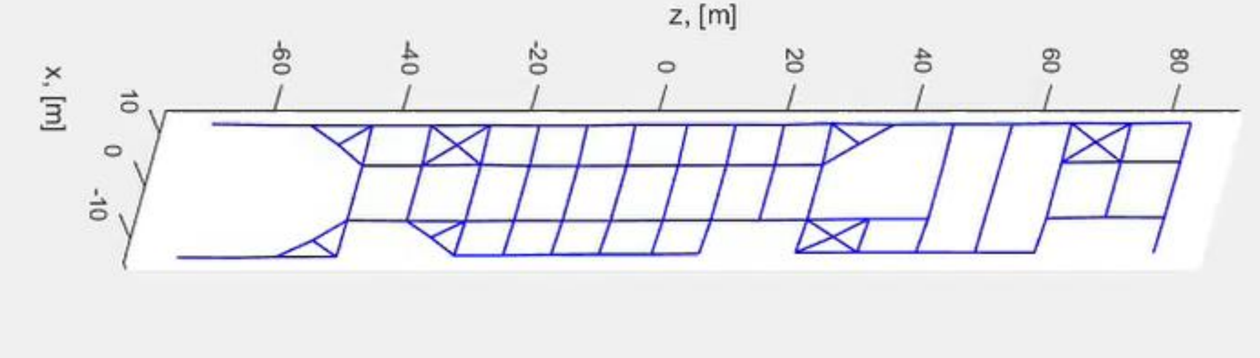


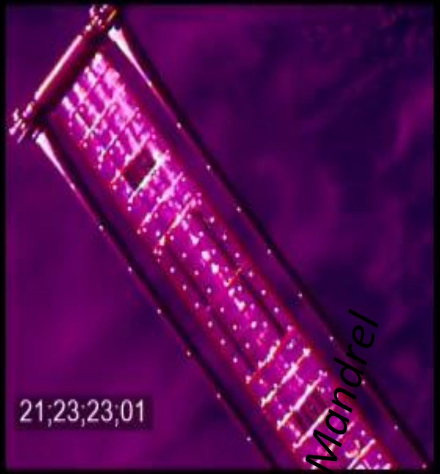
Reconstructed
0.91 Hz Day-Only Blanket Mode

Reconstruction from Accelerometer Data



Reconstruction from Photogrammetry Data





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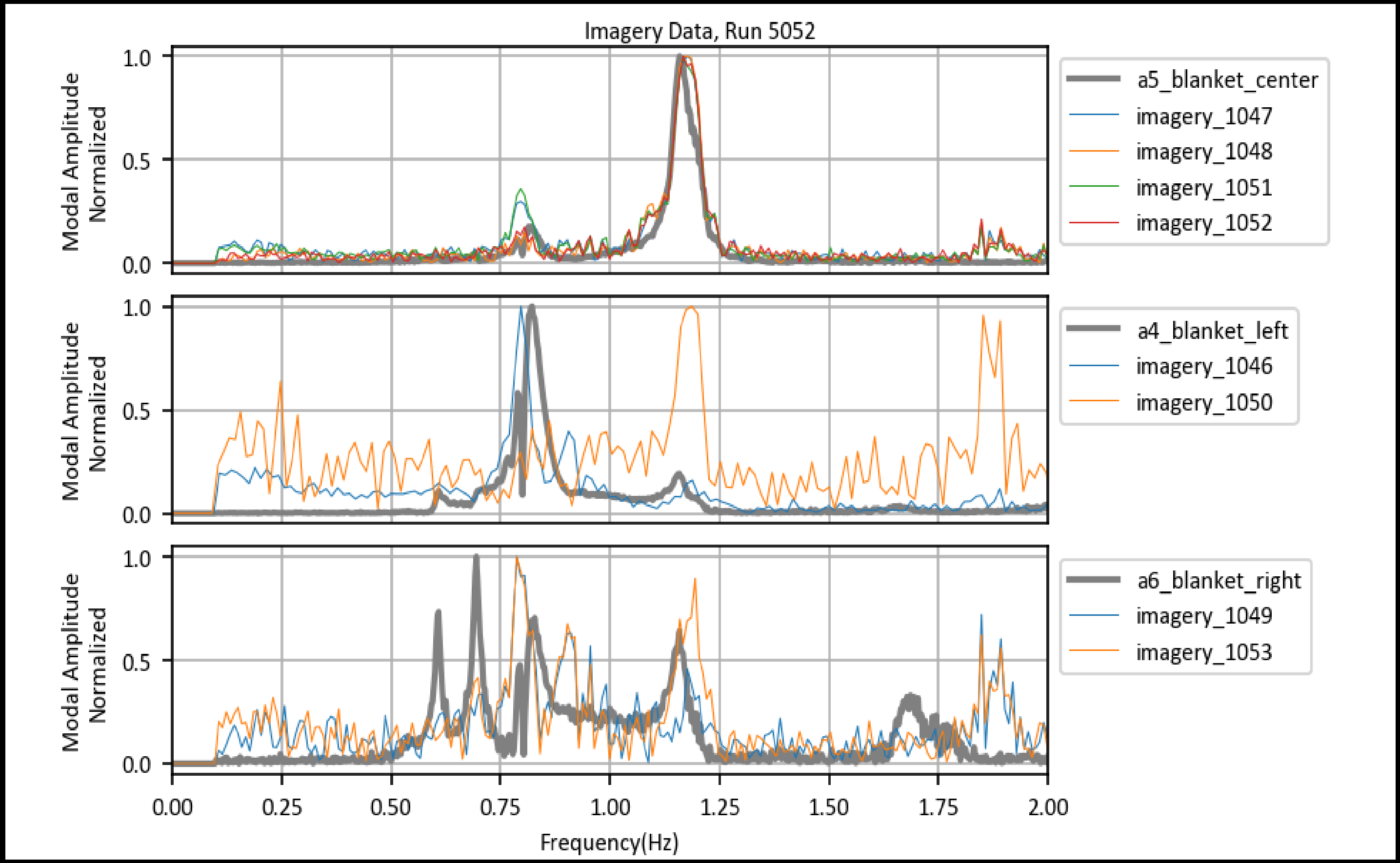
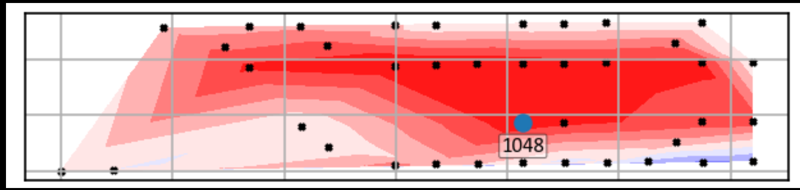
Analysis of Run 5052

Comparison of Accelerometer and Nearby Photogrammetry Target FFTs

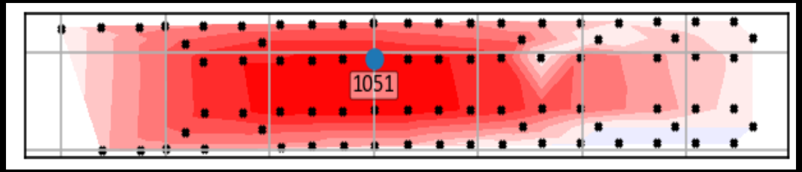


- Low-frequency night blanket run
- Large response at potential shifting mode

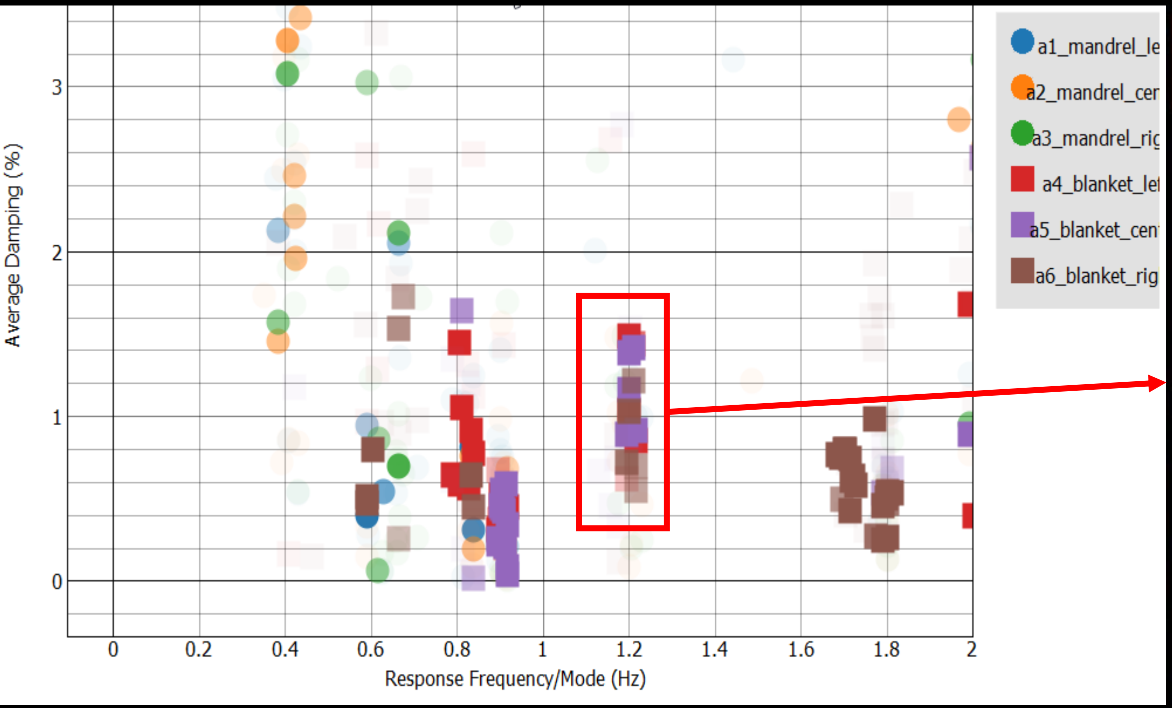
Contour for 1.17 Hz Mode from Run 5052



Contour for 0.89 Hz Mode from Run 5026

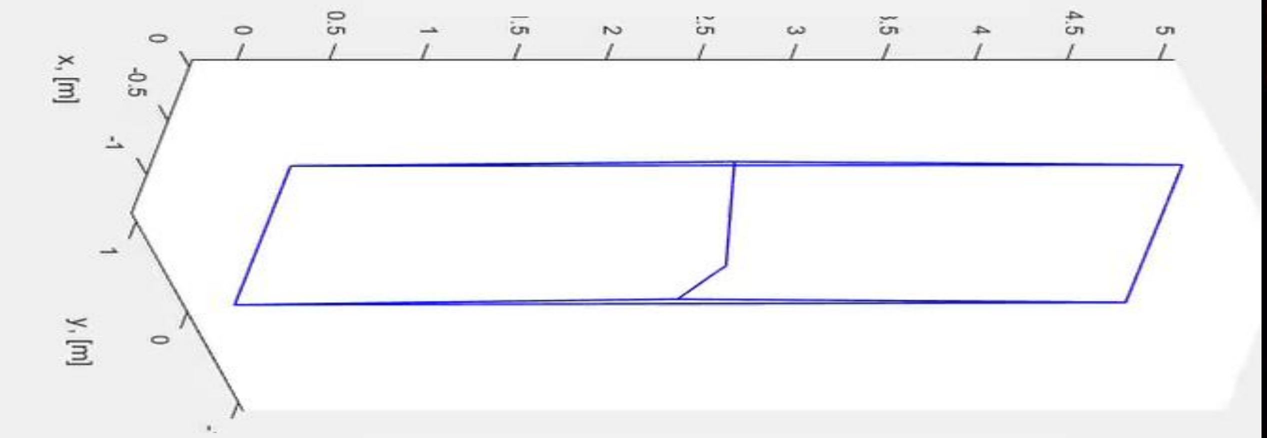


Night-Only Blanket Mode at 1.2 Hz

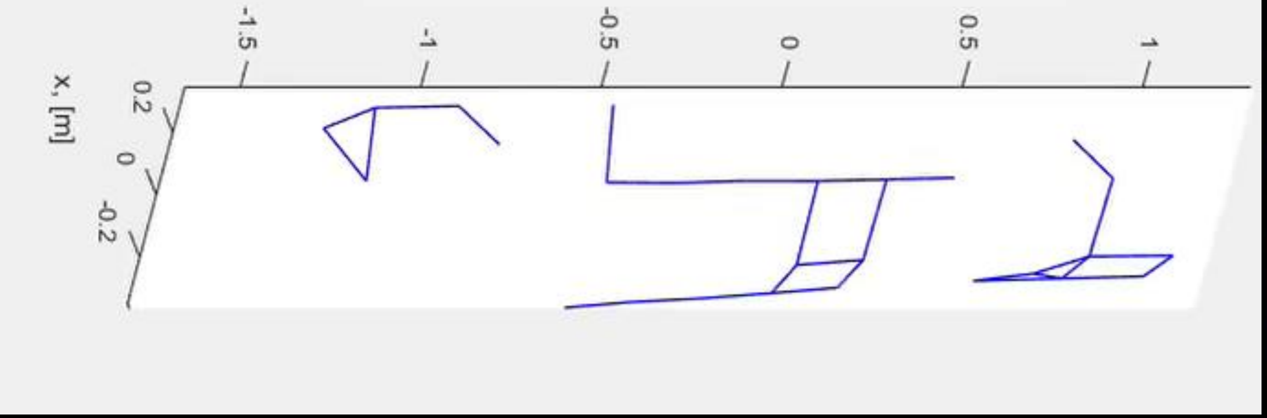


Reconstructed
1.2 Hz Night-Only Blanket Mode

Reconstruction from Accelerometer Data



Reconstruction from Photogrammetry Data



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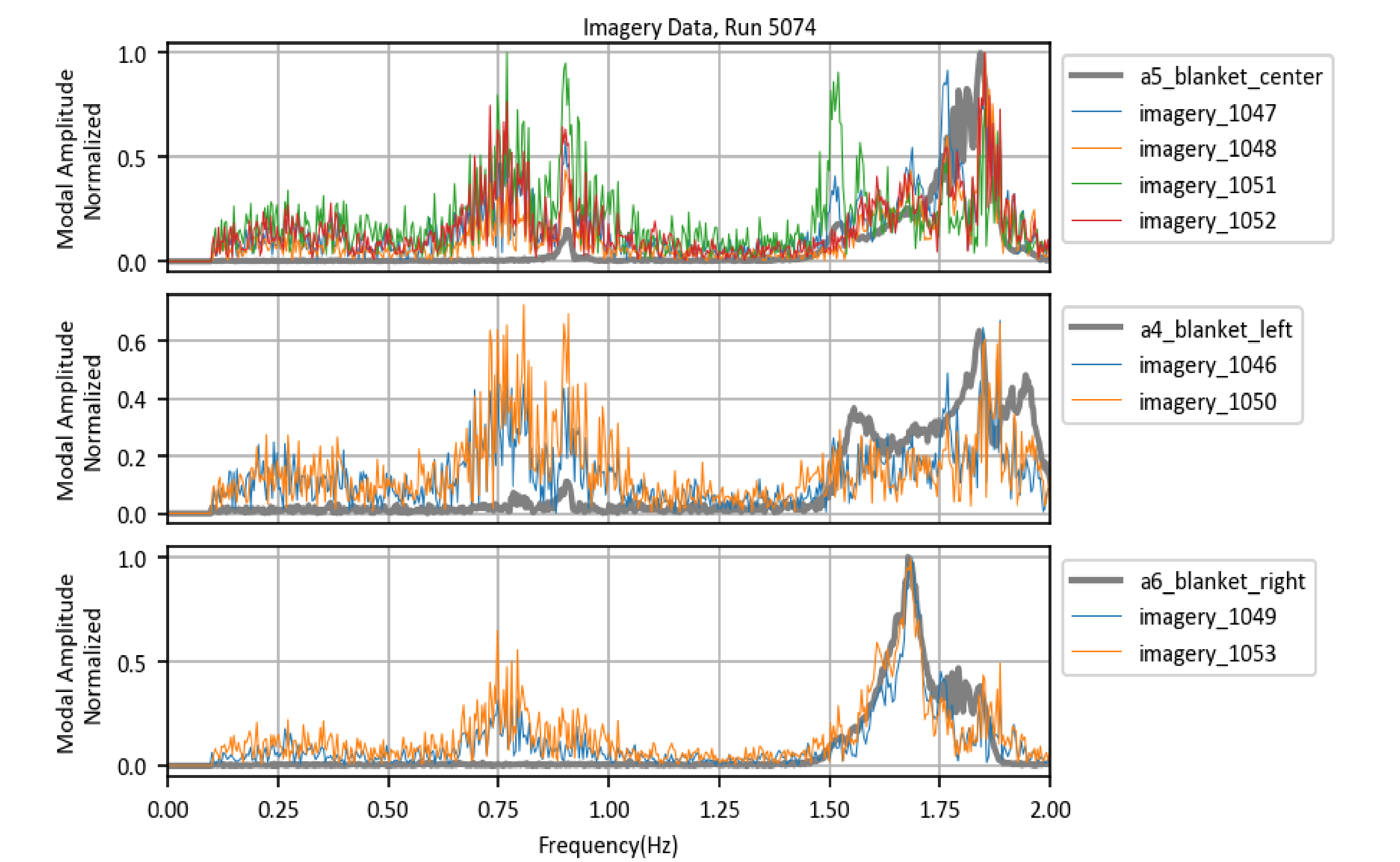
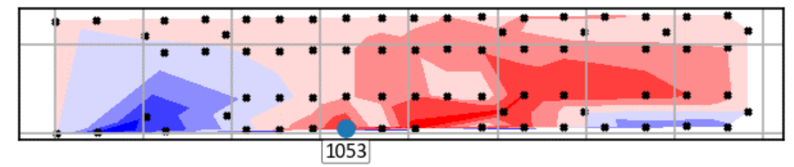
Analysis of Run 5074

Comparison of Accelerometer and Nearby Photogrammetry Target FFTs

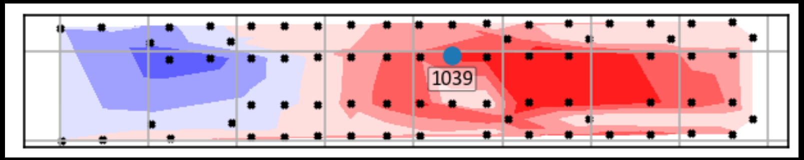


- High frequency daytime blanket run
- Large response at several modes

Contour for 1.64 Hz Mode from Run 5074



Contour for 1.83 Hz Mode from Run 5074



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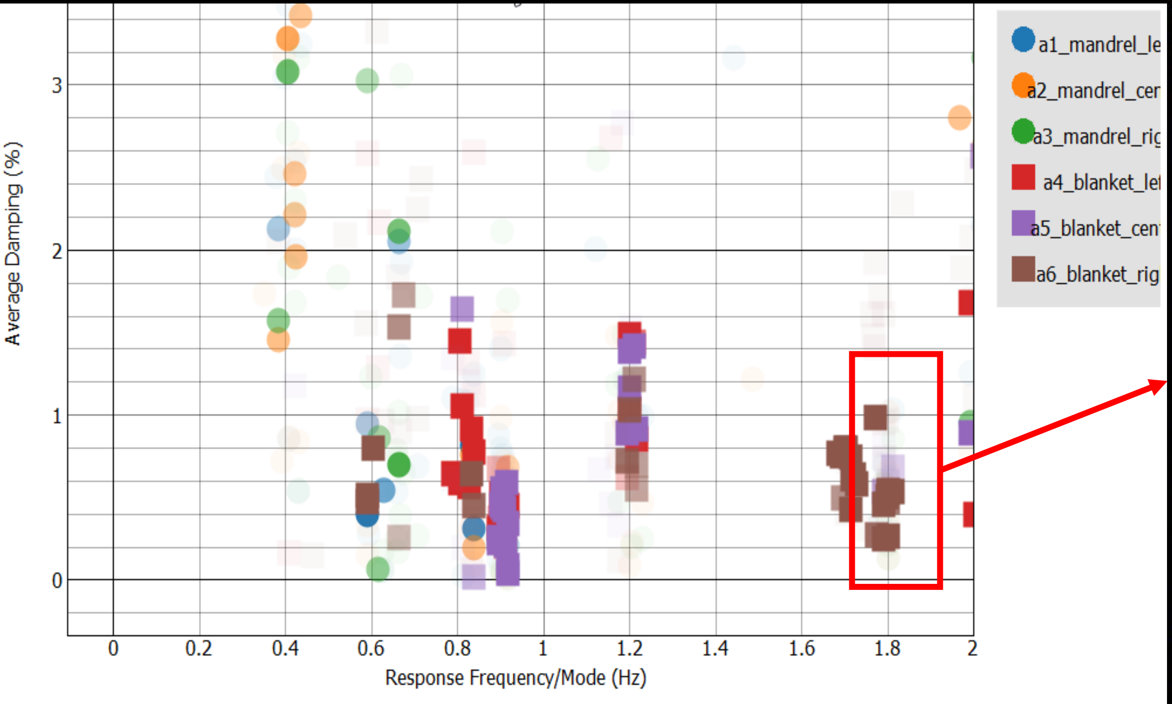
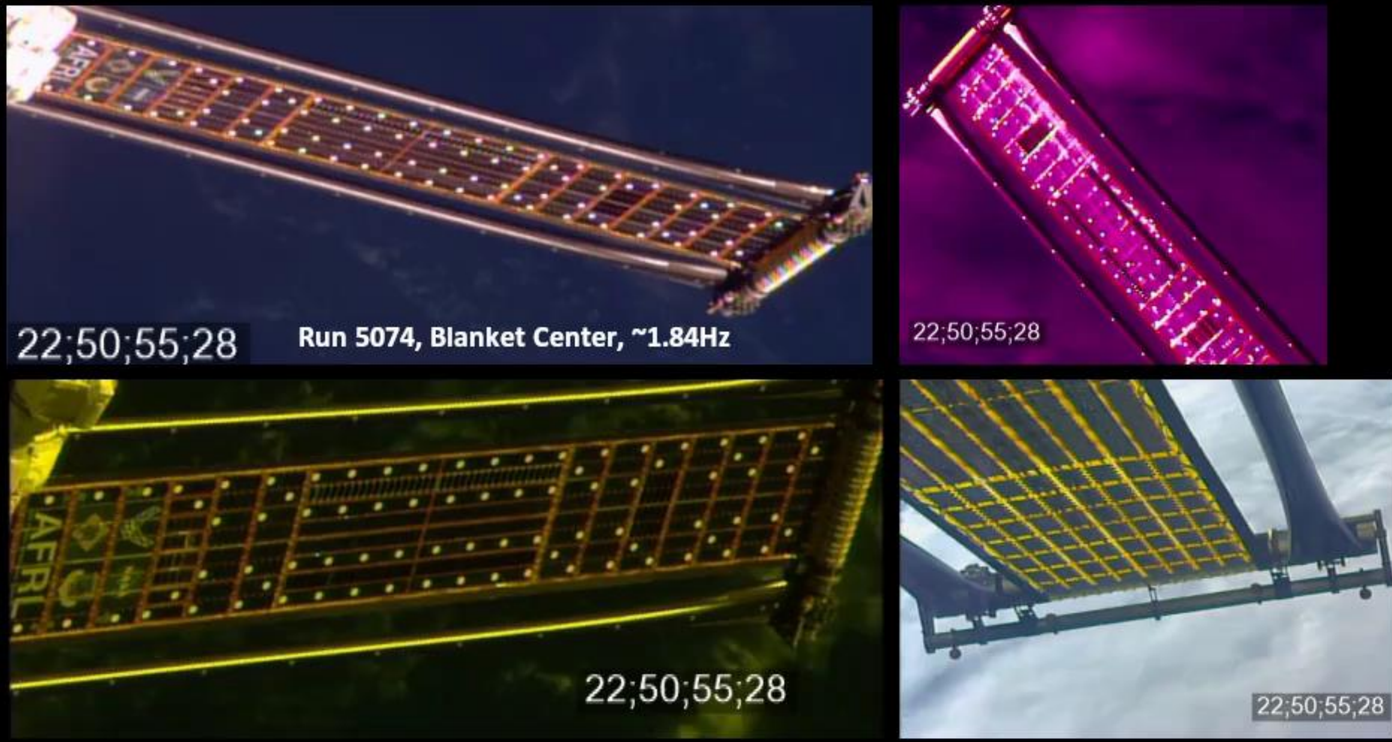
High Frequency Blanket Mode at 1.83 Hz





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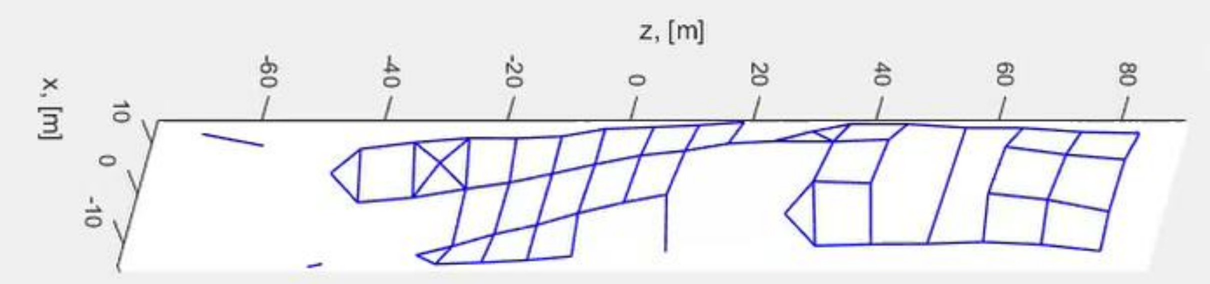
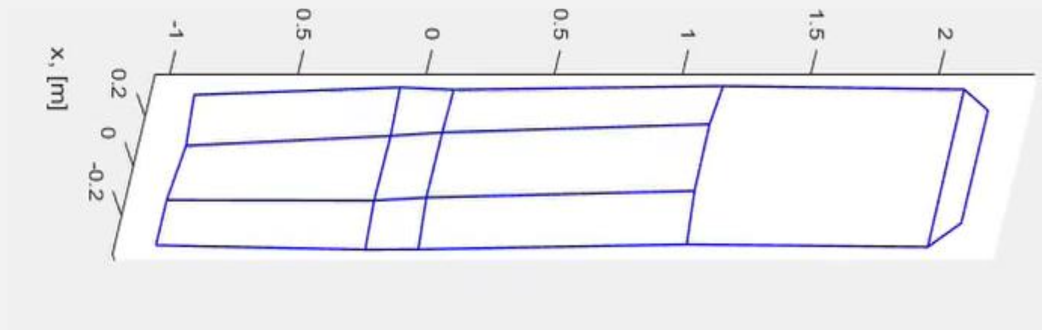
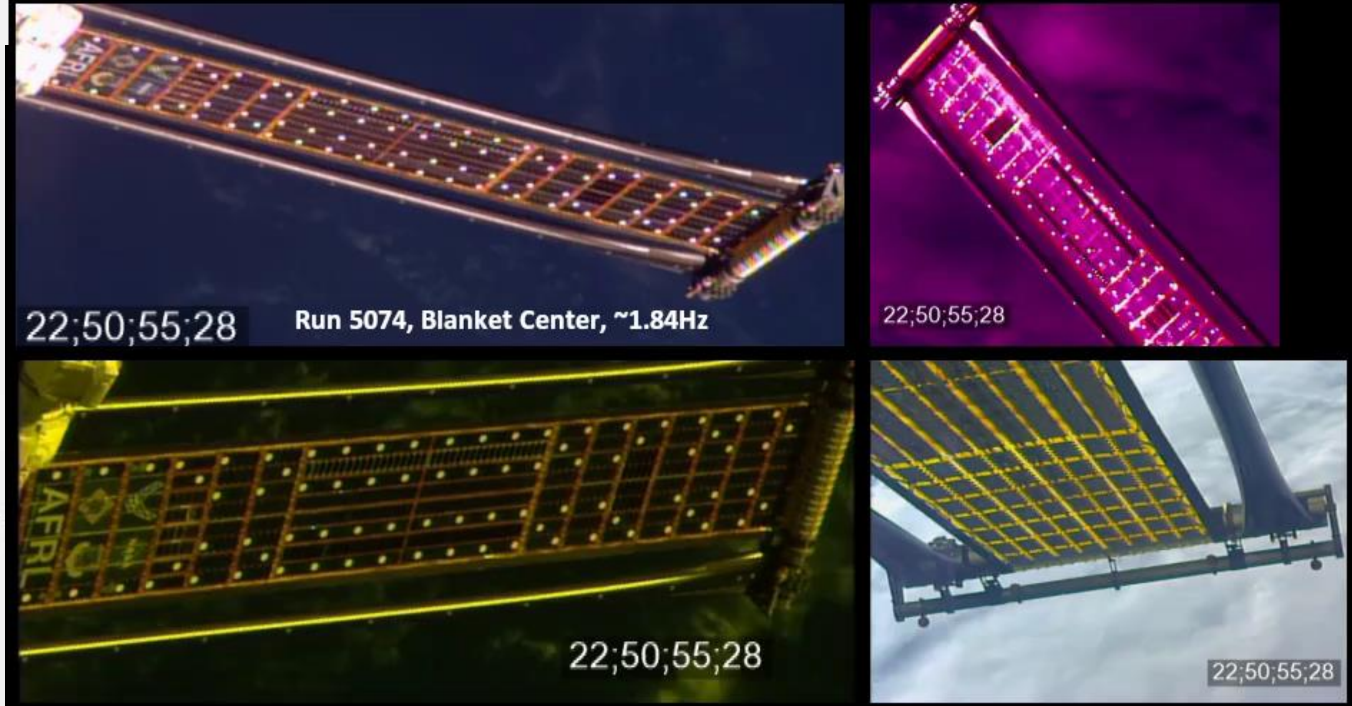
Reconstructed
2nd Order Drum Mode at 1.83 Hz

1.82 Hz Reconstruction from Photogrammetry Data (LaRC Data, Run 81/5074)



1.847 Hz Reconstruction from Photogrammetry Data (JSC Data, Run 81/5074)





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Comparison of Analytical Results

System Mode	Based on Accelerometer Data		Based on Photogrammetry Data		Damping [%]
	Frequency [Hz]	Previously Assumed Mode Shape	Frequency [Hz]	Confirmed Mode Shape	
1	0.41	1st structural bending	0.39	1st structural bending “diving board”	3.50
2	0.60	Blanket right edge w/ torsion	0.61	1st structural torsion and right blanket edge flap	3.90
3	0.66	Blanket right edge w/ torsion	0.66	1st structural torsion and right blanket edge flap	1.60
4	0.81	Blanket left edge and center	0.78	Left blanket edge flapping	1.70
5	0.91 *	Blanket drum/saddle (day)	0.89 *	1st blanket drum/saddle (day)	0.85
6	1.18 *	Blanket drum/saddle (night)	1.14 *	1st blanket drum/saddle (night)	1.55
7	1.71	Blanket right edge	1.64	3rd order right blanket edge flap	0.70
8	1.80	Blanket right edge	1.83	2nd order blanket drum/saddle	1.05

*** Indicates a mode that may be only present during the day or night**

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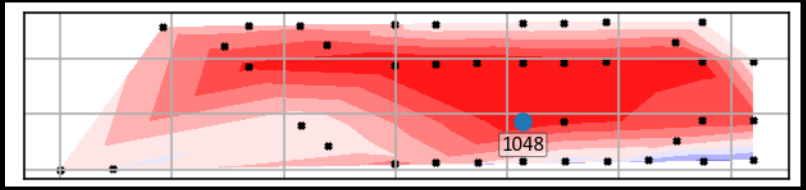
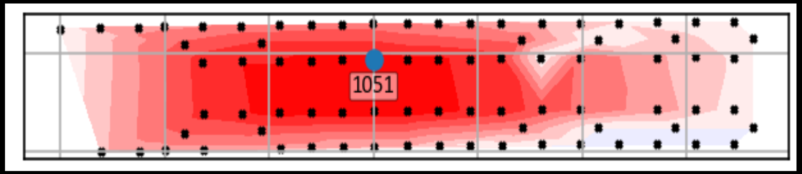
Photogrammetry Results Discussion

- Highly successful utilization of photogrammetry for characterization of structural dynamics in space
- Ongoing analysis shows excellent correlation between frequencies of modes identified using accelerometer data and photogrammetry-based position data
- Shapes of blanket modes are now more fully understood
- 0.9 Hz day and 1.17 Hz night modes *may not* be a single mode shifting
- This was a limited analysis of only four runs
- Larger conclusions about origins of low first bending mode and high damping are not possible because of problems resolving FRAM targets

Contour for 1.17 Hz Mode from Run 5052



Contour for 0.89 Hz Mode from Run 5026



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Summary of ROSA Structural Dynamics
(Based on Photogrammetry *and* Accelerometer Data)

- At least 8 structural modes identified below 2 Hz
- Consistent dynamics over 4.5 days and 200+ orbits
- Some unexpected dynamics observed:
  - Low first structural mode with high damping
  - Uneven blanket modes
- Very little measurable thermal-structural interaction during eclipse entry / exit
- Some day/night difference in blanket modes
  - Shifts in frequency
  - Some modes may shift more significantly or only appear in one lighting situation
- Photogrammetry analysis ongoing

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Future Work

- More careful measurement of damping:
  - Decay measurements from photogrammetry and LaRC processed data
- Re-examination of base motion using photogrammetry
- More careful comparison of predicted and measured modes:
  - In an ideal world, would process more photogrammetry data, try other algorithms for processing
  - Try comparing predicted FEM modes to photogrammetry modes and accelerometer modes numerically using XORTHO
  - Calibration of FEM
  - More detailed examination of night/day modes

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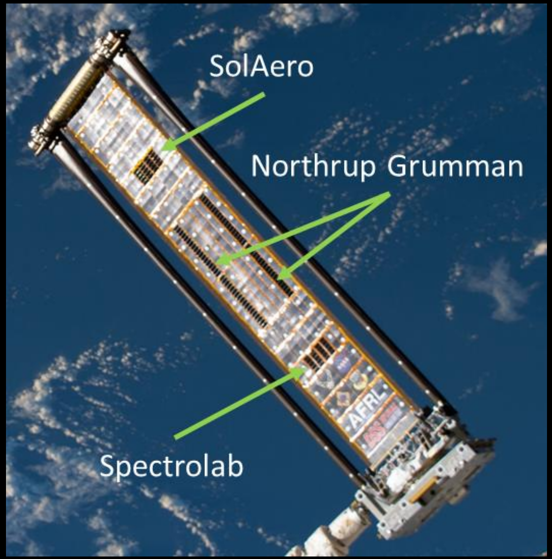
ROSA-Specific Lessons Learned

- Integrated structural modes should have been more carefully investigated
  - Likely ROSA and SPDM had similar first modes
  - Failure of FRAM accelerometer unfortunate
- Lighting in LEO on ISS is challenging
  - Glint on composites, metallics can obscure targets, confuse eyes
  - Changes in lighting during experiments significant enough to frustrate photogrammetric analysis
- Instrumentation of tension springs would have helped diagnose blanket mode anomalies



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General Lessons Learned

- Extremely thorough pre-test modeling can pay off
  - Photogrammetry predictions were a bright spot
  - Missing structural interactions was a negative
  - Having models on hand was helpful
- Simple goals and experiments work the best *"Often the most valuable experiments were those that focused on measuring single phenomena that could not be measured on the ground."* (Wada and Lou, 2002)
- Thorough and redundant instrumentation is especially important if anything goes wrong
  - Redundant instrumentation for dynamics was beneficial to fill information gaps
  - Photographs and video were invaluable in diagnosing issues
- Always budget for post-flight analysis!!!

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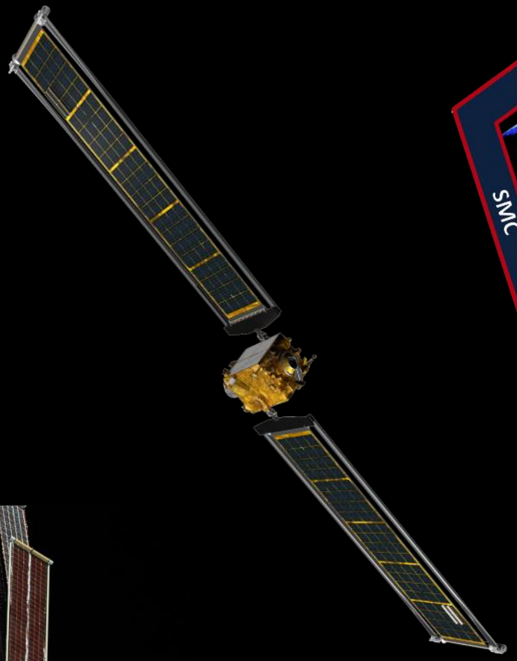
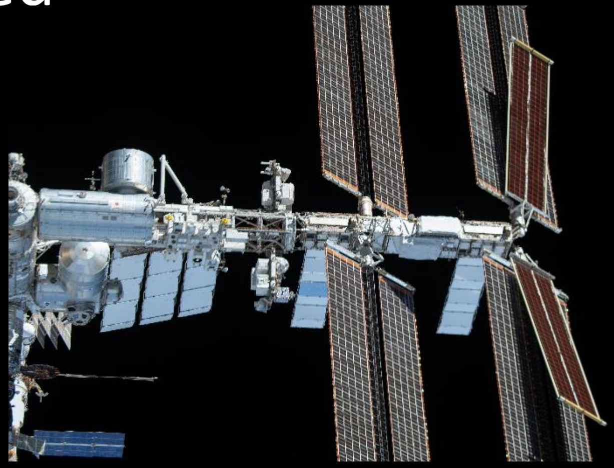
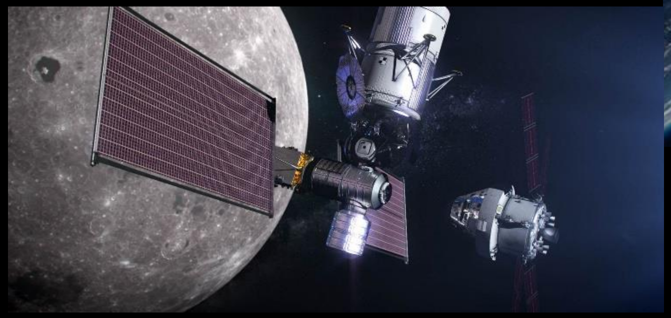
Developments Since 2017



- Double Asteroid Rendezvous Technology (DART) mission – Launched in 2021
- ISS Power Augmentation – First set launched in 2021
- Ovzon 3 geostationary satellite – Scheduled for launch in 2022
- Gateway PPE Solar Arrays – Scheduled for launch in 2024





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Roles and Responsibilities in ROSA Flight Experiment

Funding
Air Force Research Laboratory
Space Vehicles Directorate
U.S. Air Force Space and Missile Systems Center

System Design, Development, and Testing
Deployable Space Systems, Inc.

Composite Boom Development, Construction, and Testing
LoadPath, LLC
AFRL

Data Acquisition and Control System
Ecliptic Enterprises Corp

Integration and Interfaces
DoD Space Test Program

Launch:
NASA (Brokered by DoD Space Test Program)

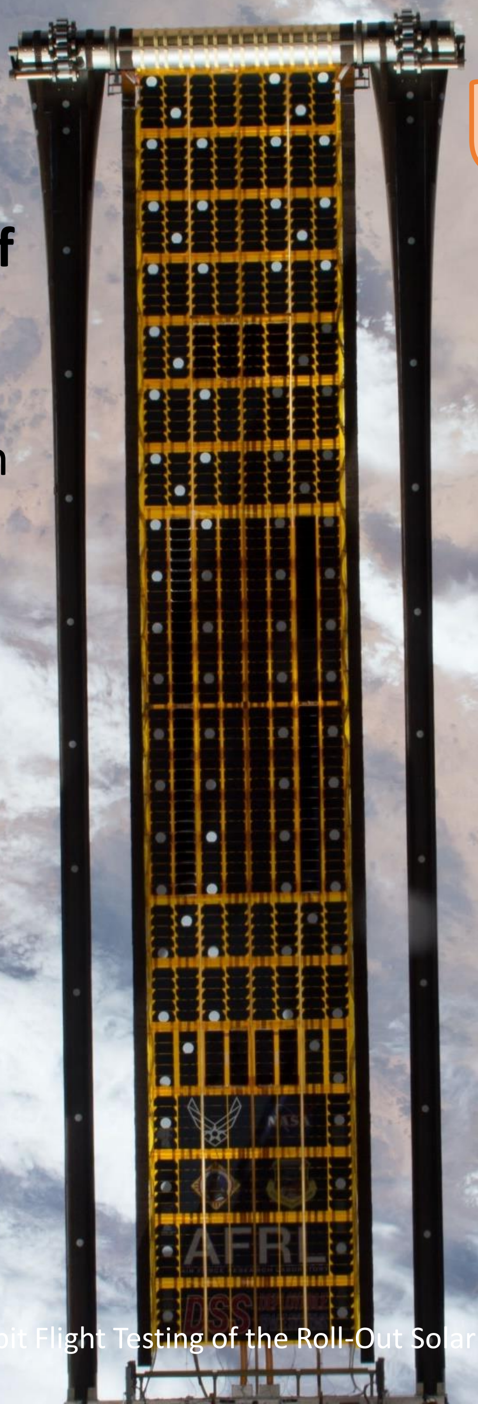
Structural Analysis
LaRC Structural Dynamics Branch (D322)
Deployable Space Systems, Inc

Photogrammetry
LaRC Advanced Measurements and Data Systems Branch (D304)
JSC Image Science and Analysis Group

Thank You!

We gratefully acknowledge the support of

- U.S. Air Force Research Laboratory Space Vehicles Directorate
- Department of Defense Space Test Program Houston
- Deployable Space Systems, Inc. (Redwire)
- LoadPath, LLC (Redwire)
- Ecliptic Enterprises Corp
- NASA Langley Structural Dynamics Branch
- NASA Langley Advanced Measurement and Data Systems Branch
- NASA Johnson Image Science and Analysis Group
- U.S. Air Force Space and Missile Systems Center



UPDATE?????

Questions?

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2. Banik, J.A., and Hausgen, P., " Roll-Out Solar Arrays (ROSA): Next Generation Flexible Solar Array Technology for DoD Spacecraft," 2017 AIAA SPACE and Astronautics Forum and Exposition, 12-14 September 2017, Orlando, Florida. AIAA-2017-5307.
3. Banik, J., Urioste, B., "Chapter 7: Spaceflight Testing," Testing Large Ultra-Lightweight Spacecraft. AIAA Progress Series in Aeronautics and Astronautics. Vol 253. 2017. pp. 215-253.
4. Chamberlain, M.K., Kiefer, S.H., LaPointe, M., and LaCorte, P., “On-Orbit Flight Testing of the Roll-Out Solar Array”, Acta Astronautica, Volume 179, February 2021, Pages 407-414.
5. Chamberlain, M.K., Kiefer, S.H., LaPointe, M. LaCorte, P., and J.A. Banik, “On-Orbit Flight Testing of the Roll-Out Solar Array”, 70th International Astronautical Congress, 21-25 October, 2019, Washington, DC, IAC-19,C3,4,1,x49723.
6. Chamberlain, M.K., Kiefer, S.H., and J.A. Banik, “Photogrammetry-Based Analysis of the On-orbit Structural Dynamics of the Roll-Out Solar Array”, 6th AIAA Spacecraft Structures Conference, AIAA SciTech Forum, 7-11 January 2019, San Diego, CA, AIAA 2019-2375.
7. Chamberlain, M.K., Kiefer, S.H., and J.A. Banik, “Structural Analysis Methods for the Roll-Out Solar Array”, 6th AIAA Spacecraft Structures Conference, AIAA SciTech Forum, 7-11 January 2019, San Diego, CA, AIAA 2019-2376.
8. Chamberlain, M.K., Kiefer, S.H., and J.A. Banik, “On-orbit Structural Dynamics Performance of the Roll-Out Solar Array”, 5th AIAA Spacecraft Structures Conference, AIAA SciTech Forum, 8-12 January 2018, Kissimmee, FL, AIAA 2018-1942.
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10. Spence, B., LaPointe, M., White, S., LaCorte, P., and S. Kiefer, “International Space Station (ISS) ROSA Solar Array Flight Experiment Mission and Results,” 36th Annual Space Power Workshop, 23-25 April 2018, Los Angeles.
11. Wada, B.K. and Lou, M., “Pre-Flight Validation of Gossamer Structures,” 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 22-25 April 2002, Denver, CO, AIAA 2002-1373.
12. Yates, H. and B. Hoang, “SSL ROSA Qualification Status,” 36th Annual Space Power Workshop, 23-25 April 2018, Los Angeles.

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Backup Slides

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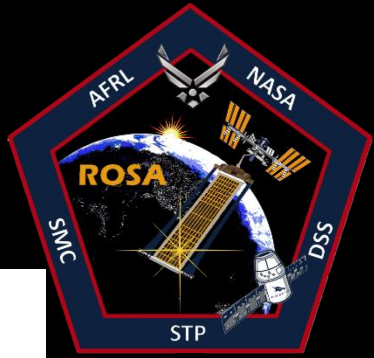
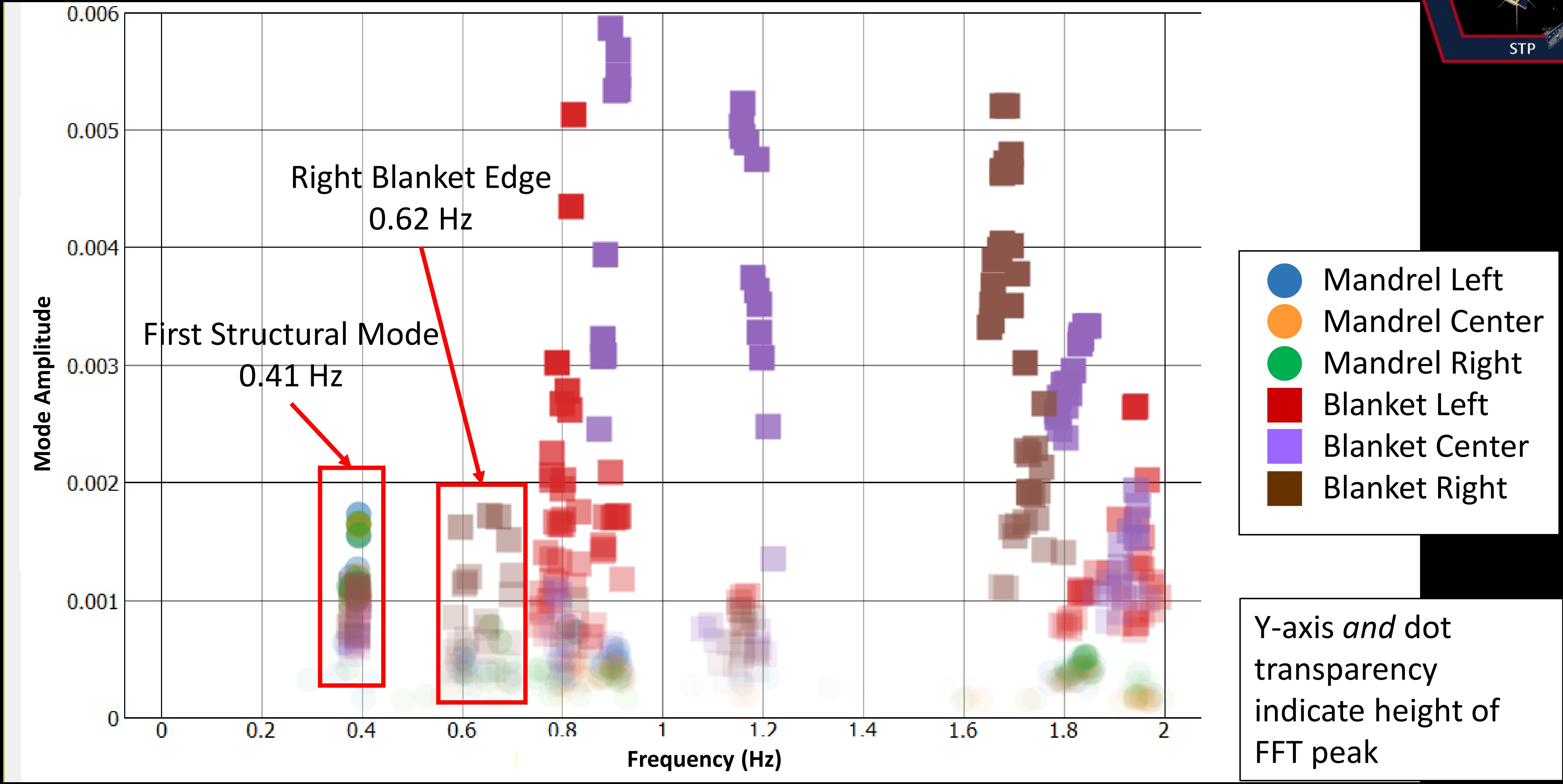


Structural Modes from Accelerometer Data



Y-axis *and* dot transparency indicate height of FFT peak

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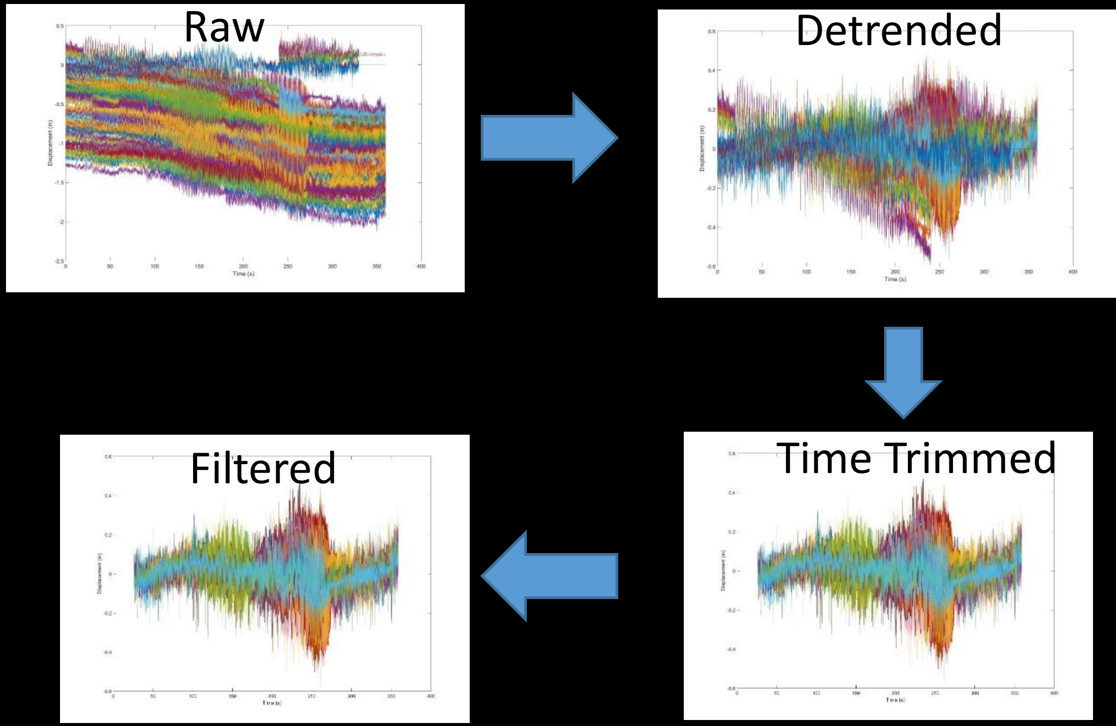
Photogrammetry Data Processing

- Data delivered as time histories of locations of each available target
- Processing:
  - Converted to displacements
  - Removed offsets and linear trends
  - Trimmed for time period of interest
  - Band-pass filtered around modes of interest



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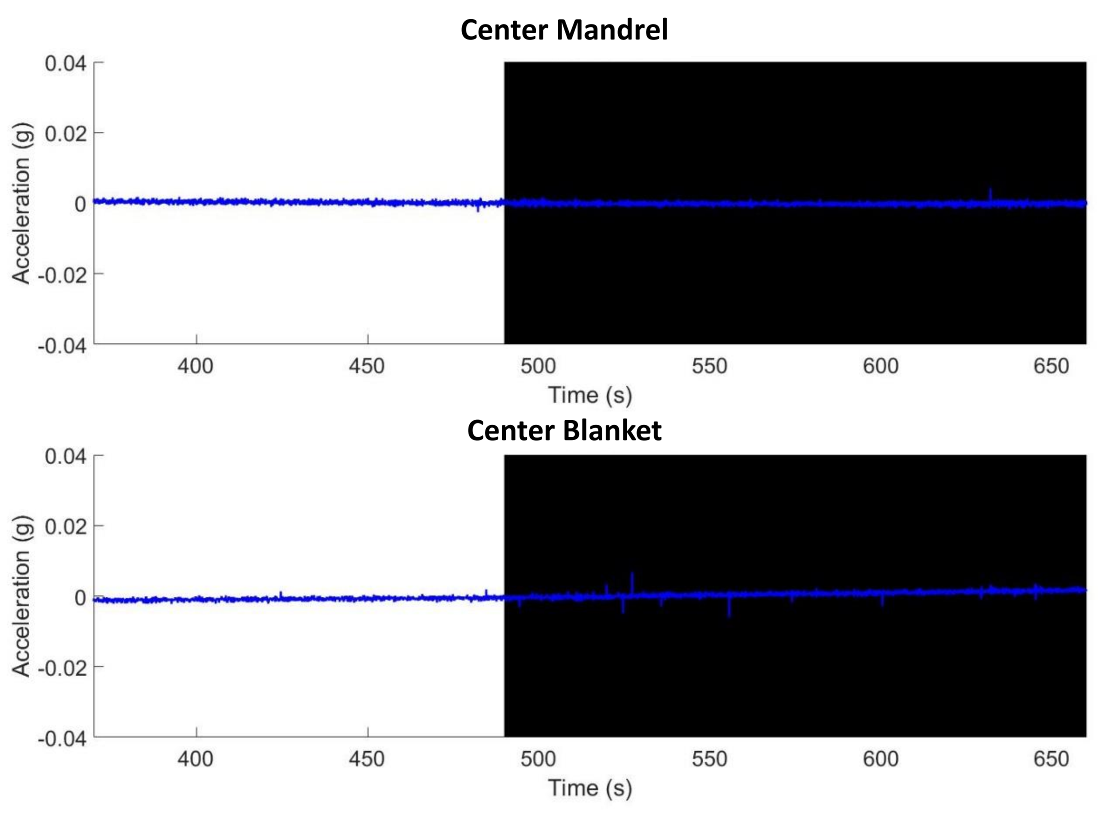
Eclipse Dynamics

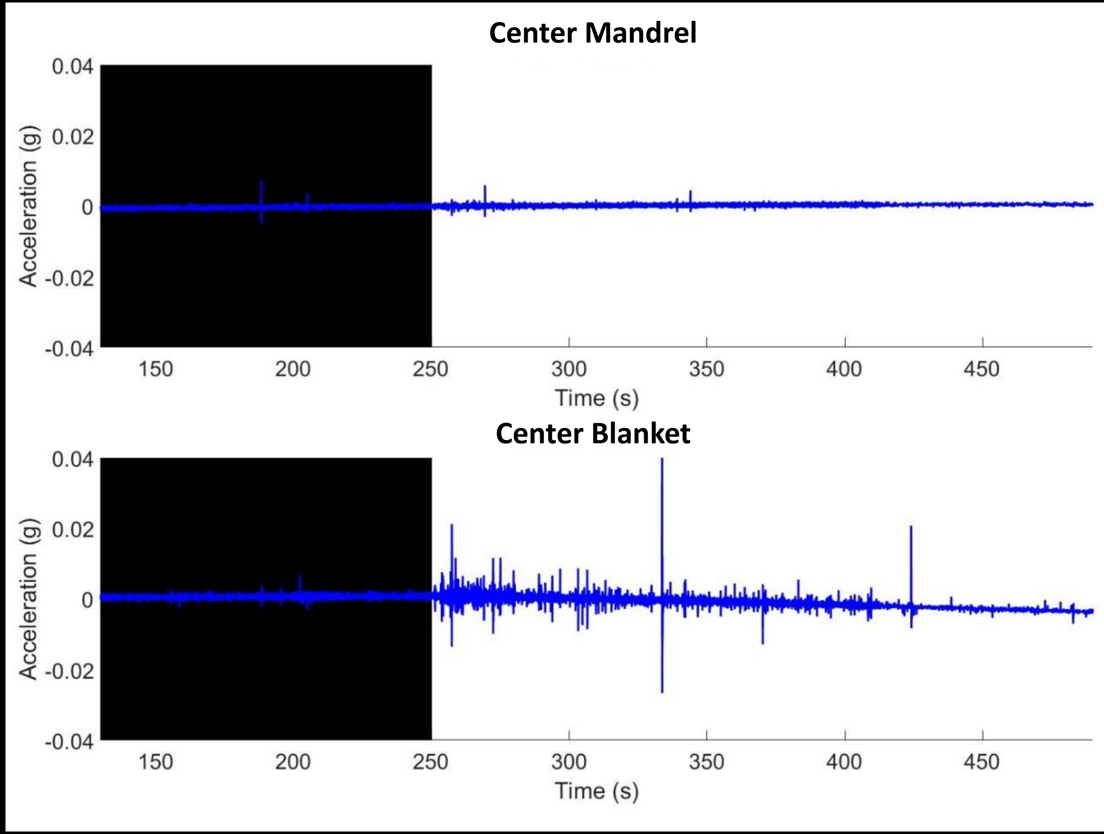
Eclipse Entry

- No noticeable dynamics above noise during entry
- Accelerometers show very small temperature-dependent trend

Eclipse Exit

- Some dynamics seen in blanket accelerometers only
- Frequencies excited are much higher than primary structural modes





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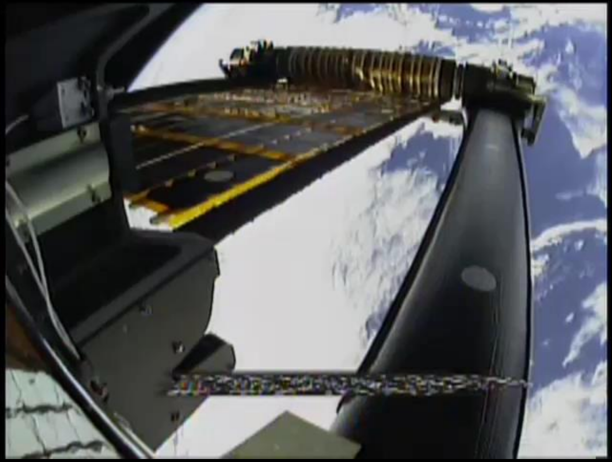
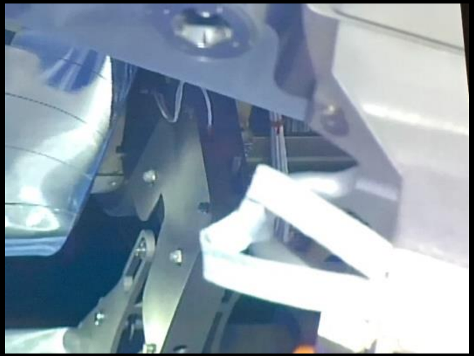
ROSA Retraction Issue





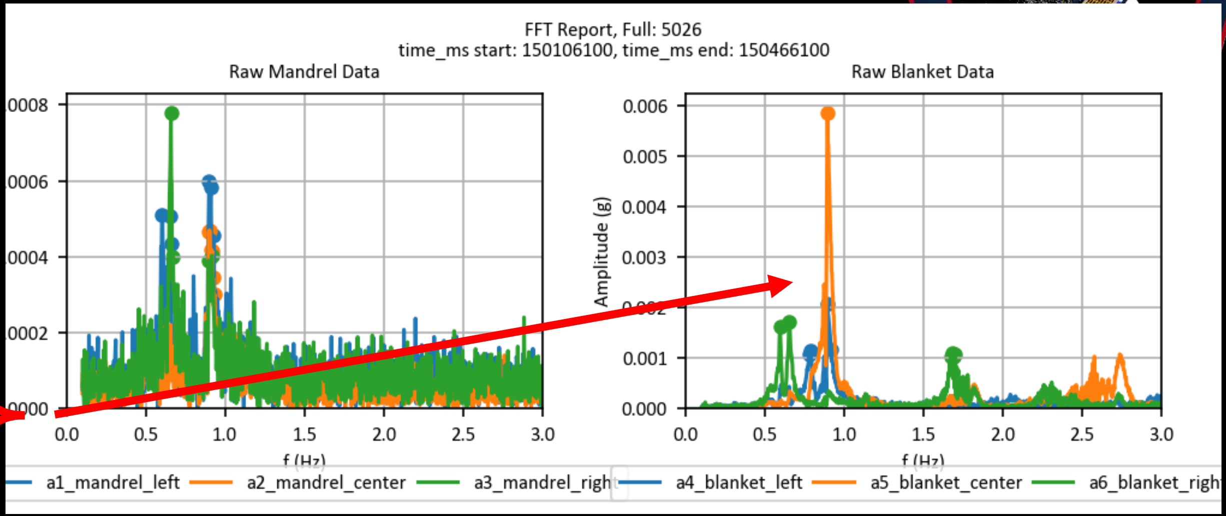
- ROSA was to be disposed by retracting and returning to Dragon trunk (ISS housekeeping requirement)
- Retraction attempted overnight June 24^{th} – 25^{th}, 2017
- For safety reasons, two verified latches were required
- Noticeable “telescoping” of blanket and booms as it rolled up
- Latches lined up crooked, tolerances exceeded, could not latch
- Small retraction steps failed, redeployment initiated
- 2 more retraction attempts made*

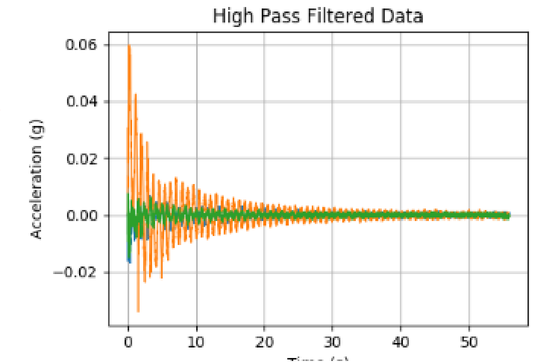
- Retraction on ground had proven dicey, hard to offload accurately

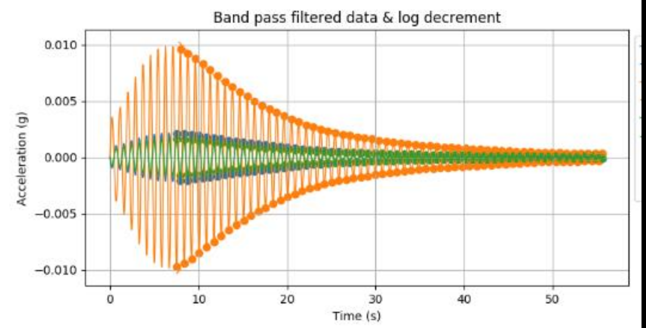
**Because of retraction latching issue, ROSA actually deployed four times on orbit*

Individual-Accelerometer Method

- Steps:
  - Compute Fast Fourier Transform (FFT)
  - To find modes:
    - Band-pass filter whole data set 0.1 to 3.0 Hz
    - Use peak-finding to identify up to three modes
  - To find damping:
    - High-pass filter free decay data at 0.1 Hz
    - Band-pass filter ± 5% around each mode
    - Logarithmic curve fit to time history
    - Damping recorded only for good curve fits
- Used to analyze 33 of the data sets
- Interactive plotting tools used to identify trends
- 1,039 modes identified in excited data
- Damping calculated for 972 modes







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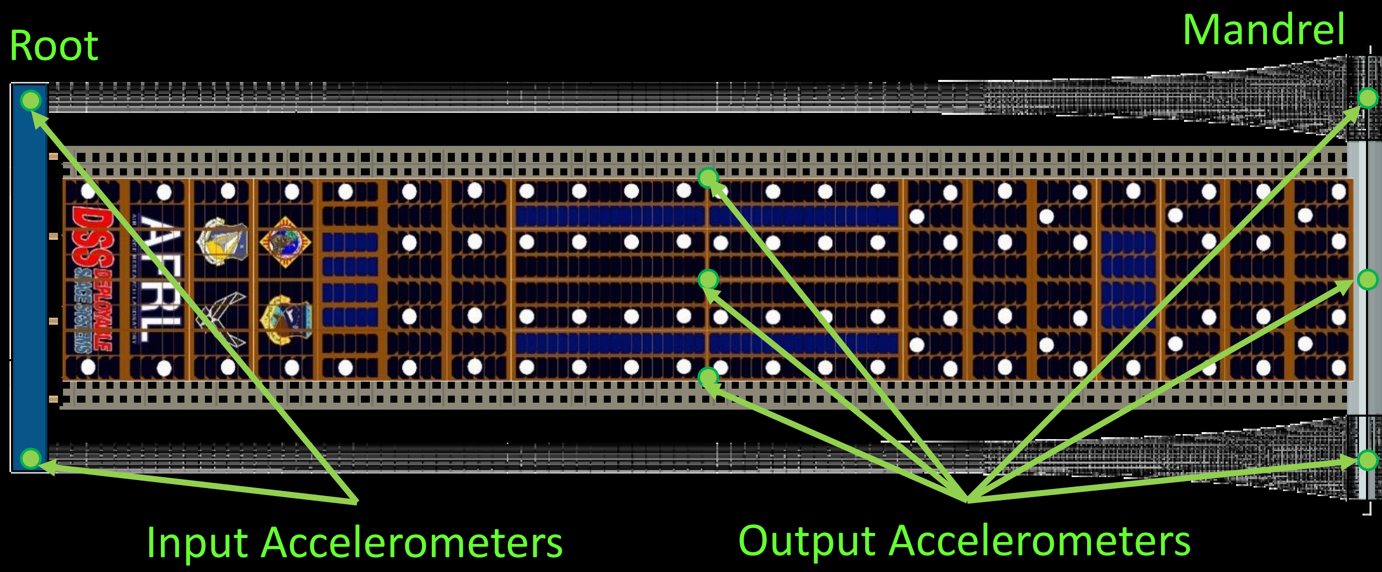
Eigenvalue Realization Algorithm (ERA) Approach

- ERA Modal ID suite used to identify modes, mode shapes, and damping
- ERA used in time-domain setting
- For excitation data, boom root accelerometers treated as inputs
- Blanket and mandrel accelerometers treated as outputs
- ERA used to build 21 system models (10 to 30 modes)
- Modes retained if between models…
    - Damping is similar
    - Frequency is similar
    - Mode shape is similar (using MAC)
- Applied to 46 experimental runs



Juang, J.-N., Horta, L.G., and Phan, M.: “System/Observer/Controller Identification Toolbox from Input/Output Measurement Data.” User's Guide, NASA TM-107566, 1992.

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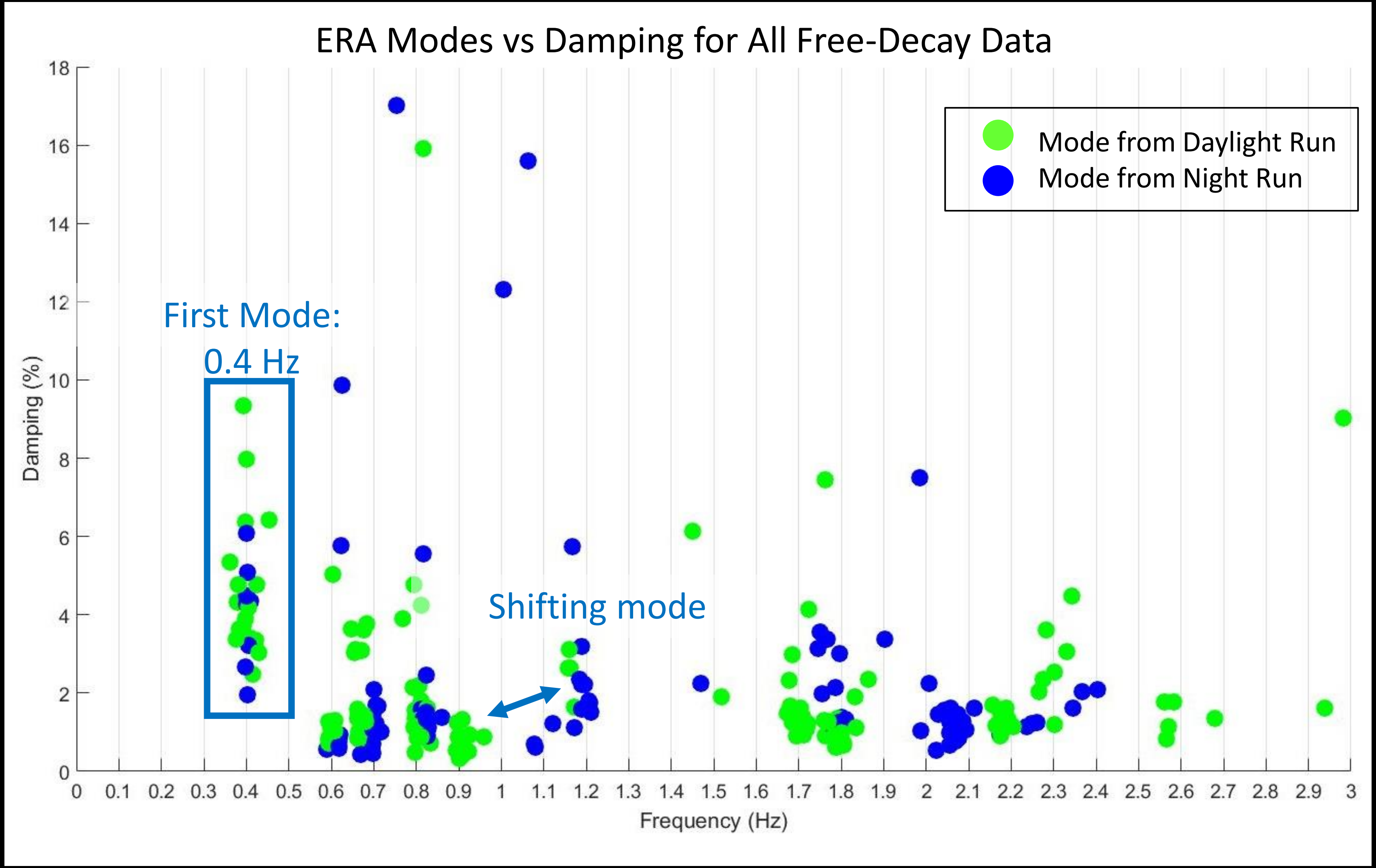
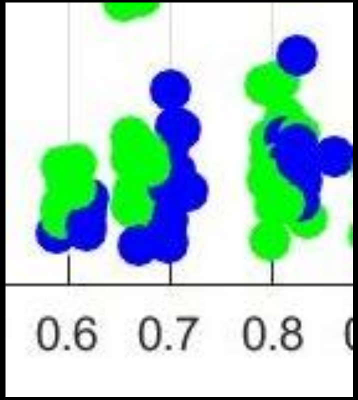
Eigenvalue Realization Algorithm Results



- Damping estimate for first mode: 4.5 %
- Three modes shift 2.5-4.5% to higher frequencies at night



- 1.17 Hz mode and 2.06 Hz mode appear only during night
- 0.91 Hz and 2.18 Hz modes appear only during day